Research Centre on
ZERO EMISSION
NEIGHBOURHOODS
IN SMART CITIES

FLEXor

The development of simulation and optimization models for energy-flexible operation in the built environment

ZEN REPORT No. 75 – 2025

Benjamín Manrique Delgado, Harald Taxt Walnum, Marius Bagle, Åse Sørensen, Luis Caetano, Reidar Kind, Igor Sartori | SINTEF

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Keywords: Energy flexibility, load profiles, demand response, optimal building operation.

Norwegian University of Science and Technology (NTNU) | www.ntnu.no
SINTEF Community | www.sintef.no

https://fmezen.no

Preface

Acknowledgements

This memo has been written within the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN). The authors gratefully acknowledge the support from the Research Council of Norway, the Norwegian University of Science and Technology (NTNU), SINTEF, the municipalities of Oslo, Bergen, Trondheim, Bodø, Bærum, Elverum and Steinkjer, Trøndelag county, Norwegian Directorate for Public Construction and Property Management, Norwegian Water Resources and Energy Directorate, Norwegian Building Authority, ByBo, Elverum Tomteselskap, TOBB, Snøhetta, AFRY, Asplan Viak, Multiconsult, Civitas, FutureBuilt, Heidelberg Materials, Skanska, GK, NTE, Smart Grid Services Cluster, Statkraft Varme, Renewables Norway and Norsk Fjernvarme.

The Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities

The ZEN Research Centre develops solutions for future buildings and neighbourhoods with no greenhouse gas emissions and thereby contributes to a low carbon society. Researchers, municipalities, industry and governmental organizations work together in the ZEN Research Centre in order to plan, develop and run neighbourhoods with zero greenhouse gas emissions. The ZEN Centre has nine pilot projects spread over all of Norway that encompass an area of more than 1 million m2 and more than 30 000 inhabitants in total.

In order to achieve its high ambitions, the Centre will, together with its partners:

- Develop neighbourhood design and planning instruments while integrating science-based knowledge on greenhouse gas emissions;
- Create new business models, roles, and services that address the lack of flexibility towards markets and catalyze the development of innovations for a broader public use; This includes studies of political instruments and market design;
- Create cost effective and resource and energy efficient buildings by developing low carbon technologies and construction systems based on lifecycle design strategies;
- Develop technologies and solutions for the design and operation of energy flexible neighbourhoods;
- Develop a decision-support tool for optimizing local energy systems and their interaction with the larger system;
- Create and manage a series of neighbourhood-scale living labs, which will act as innovation hubs and a testing ground for the solutions developed in the ZEN Research Centre. The pilot projects are Furuset in Oslo, Fornebu in Bærum, Sluppen and Campus NTNU in Trondheim, Mære Campus, Ydalir in Elverum, Campus Evenstad, Ny by-ny flyplass Bodø, and Zero Village Bergen.

The ZEN Research Centre is a eight year project ending in 2025, and the budget is approximately NOK 380 million, funded by the Research Council of Norway, the research partners NTNU and SINTEF, and the user partners from the private and public sector. The Norwegian University of Science and Technology (NTNU) is the host and leads the Centre together with SINTEF.

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Abstract

Energy flexibility refers to the ability of a building or neighbourhood to activate its on-site flexibility sources (building's thermal mass, heat storage tanks, batteries, EV charging) while safeguarding user needs and comfort. FLEXor is an optimization tool for flexible energy use, storage and generation in buildings, that generates optimal load profiles in response to grid signals, such as dynamic energy prices, thus facilitating energy planning and optimal system dimensioning and control It comprises interconnected models that handle user inputs, activate sub-models, and define system topology. These include component models (building envelope, hot water tank, heat sources, EV charging, PV systems and electric batteries), functional models (energy costs, fixed energy demand), and a model for typical demand profiles It is implemented in Python and uses the Pyomo software package for formulating, solving and analyzing optimization models.The tool is available in a backend solution, run on a SINTEF server, while their frontend is accessible in two ways: via a Web App, and via API (Application Programming Interface) for more advanced users and for use by other software.

FLEXor is a three-level model. The top model reads the user input, collects and organizes the input parameters and input data, sets up and activates the second- and third-level models, and collects and organizes the results. This model is not interchangeable. The second-level model sets up the system topology in the building used to define the connections between the energy components in the building. This model is interchangeable. The third-level models have several different purposes. These include component models, such as the building envelope, domestic hot water (DHW) tanks, electric batteries, heat sources (e.g. direct electric heaters, district heating, and heat pumps), electric vehicle charging, and onsite PV systems; functional models to calculate energy costs, fixed energy demand, the Linear Time-Invariant (LTI) model structure; and a model to calculate energy demand profiles via PROFet.

The starting point is given by typical (non-flexible) energy demand load profiles taken from PROFet, based on a statistical analysis of hourly measurements from several buildings classified in different categories. The flexibility sources are modelled as internal variables (the model's states) such as indoor temperature, tank temperature, battery state of charge, and are subject to boundary conditions and constraints that represent user comfort and user needs, such as a comfort band for indoor temperature, a lower bound for the hot water tank's temperature, and the charging of electric vehicles within the connection time and capacity.

All the component models (third-level) in FLEXor are designed to be self-standing. Thus, they are self-contained, and do not include the control and/or optimization of other components. The models are designed to be i) linear, ii) in state space form (when applicable), and iii) transparent. This allows the high-level model to be fast, lean, relatively simple, and able to leave a component out of the optimization process if necessary.

Contents

1 Introduction

FME-ZEN spearheaded the development of innovative tools like PROFet (load profiles estimator) and FLEXor (energy flexible operation), both of which facilitate energy planning and optimal system dimensioning and control. This report describes FLEXor, while PROFet is described in Smertinas *et al.* (2025).

Unlike conventional simulation-based methods, these tools use real measurement data from a comprehensive database representing over 2.5 million square meters of building space in Norway, and can generate typical hourly load profiles for electricity and thermal energy demand (PROFet) and optimize the control of indoor temperature, water heaters, and EV charging in response to a price signal, to minimise energy cost while safeguarding user comfort (FLEXor). Both tools' calculation module is available in a backend solution, run on a SINTEF server, while their frontend is accessible in two ways: via a Web App, and via API (Application Programming Interface) for more advanced users and for use by other software.

1.1 Disposition

The report is organized as follows. Section 2 presents the structure of the FLEXor model and its components. Section 3 presents example applications of FLEXor and energy flexibility in buildings and neighbourhoods. Section 4 describes the FLEXor Web application and the main characteristics of the building archetypes.

1.2 Terminology

The terms *energy demand* and *energy use* in this memorandum follow the FME ZEN terminology. Thereby, *energy demand* is a theoretical size used to describe the energy demand linked to energy services and energy needs in buildings, such as domestic hot water, space heating, ventilation, lighting, plug loads and so on. Energy demand, as estimated by the PROFet tool (I. Sartori et al., 2021) is intended as gross energy demand, i.e. losses in the heat distribution system are included. *Energy use* is a measurable size which can be linked to both energy services and energy carriers (such as electricity, fuels, district heating etc.), which also considers other losses within the building, such as storage and conversion losses.

2 Model structure

FLEXor is a three-level model. The top model reads the user input, collects and organizes the input parameters and input data, sets up and activates the second- and third-level models, and collects and organizes the results. This model is not interchangeable. The second-level model sets up the system topology in the building used to define the connections between the energy components in the building; this is also where the objective functions are defined. This model is interchangeable, but as of time of writing only a standard building typology is available. The third-level models have several different purposes. These include component models, such as the building envelope, domestic hot water (DHW) tanks, electric batteries, heat sources (e.g. direct electric heaters, district heating, and heat pumps), electric vehicle charging, and onsite PV systems; functional models to calculate energy costs, fixed energy demand, the Linear Time-Invariant (LTI) model structure; and a model to calculate energy demand profiles via PROFet.

Energy flexibility refers to the ability of a building or neighbourhood to activate its on-site flexibility sources (building's thermal mass, heat storage tanks, EV charging) while safeguarding user needs and comfort. The activation of flexibility sources (described below) depends on the driver and the goal that is pursued (Sartori et al., 2022b). The flexibility driver considered here is a combination of energy price and grid tariff, applicable to either electricity or district heating. The energy prices are given as hourly values – typically, historical data on electricity market prices – and the grid tariff is a Peak Power Monthly (PPM). This is a grid tariff that, on top of a fix component and an energy-proportional component (*energiledd*), also has a peak power, or peak load component (*effektledd*), with which the optimizer finds the most convenient level for the monthly peak power values. Further details are given in subsection *Cost structure and calculation*.

The flexibility goals considered are Energy import minimization, Cost minimization and Flat profile, discussed also in subsection 2.2. Minimization of energy import and (energy use related) cost is intended from the end-user's viewpoint. The Flat profile goal pursues a flattening of the load profile, as much as possible while limiting the associated energy losses. Thus, the Flat profile will, at the cost of some energy loss, not only smoothen the high peaks – in a similar fashion as a Cost minimization with PPM tariff – but also avoid "deep valleys" and sudden changes in the energy demand. These features might be desirable at an aggregated scale, for a smooth operation of a grid or energy supply system.

Figure 1 shows the process through which energy demand profiles are calculated to be used as input to FLEXor, which in turn calculates flexible loads. The main tool for the first part of this process is PROFet, which is used for estimating typical load profiles based on measurements from electricity and district heating smart meters. In contrast, FLEXor is a tool for estimating the optimal flexible load profiles in response to a flexibility driver.

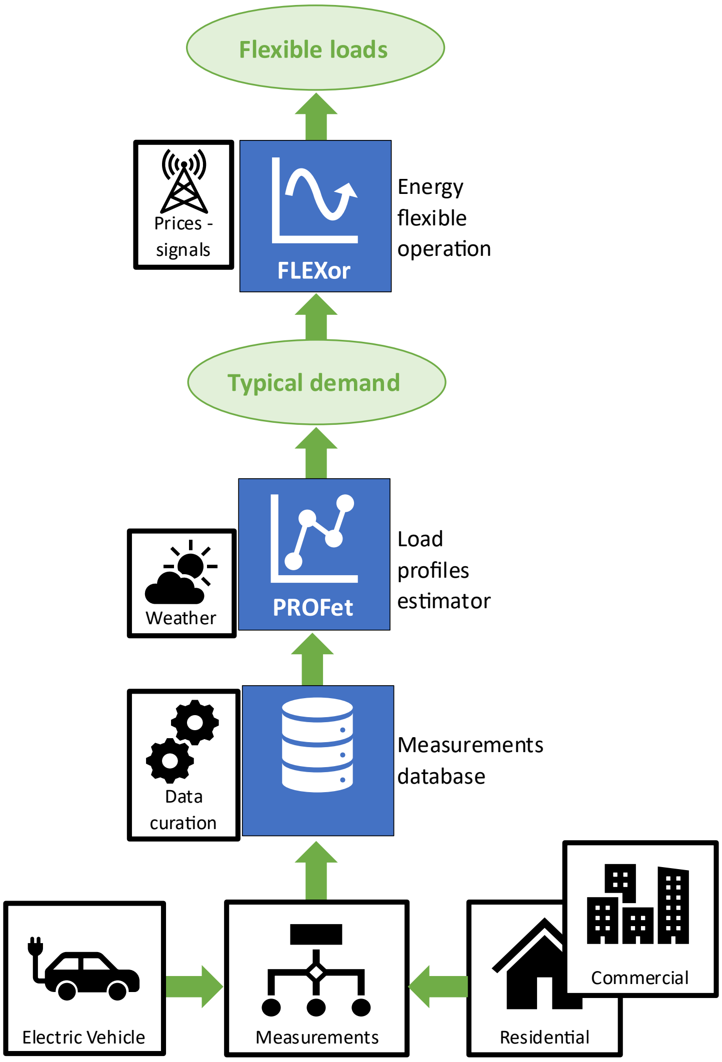

Figure 1. Schematic representation of the collection, preparation, and calculation of typical energy demand and flexible load profiles using PROFet and FLEXor.

2.1 Top-level model

The top-level model in FLEXor has five main tasks, namely to:

1. Gather, organize, and allocate the input parameters and input data.
2. Create the third-level model blocks.
3. Create the second-level model, or system equations.
4. Pass the model to the solver.
5. Gather and organize the results.

The third-level models are organized in blocks, where each block can contain one or more instances of one type of third-level model.

Figure 2 shows a schematic of the interconnections between the modules that compose FLEXor. The energy flow (represented by the thick blue lines) goes from left to right, while the calculation flow goes the opposite direction, from right to left. The calculations start with defining the Typical demand profiles that must be satisfied, obtained from PROFet, and continue through a series of flexibility options until obtaining the Flexible load profiles on the energy carriers that supply the building.

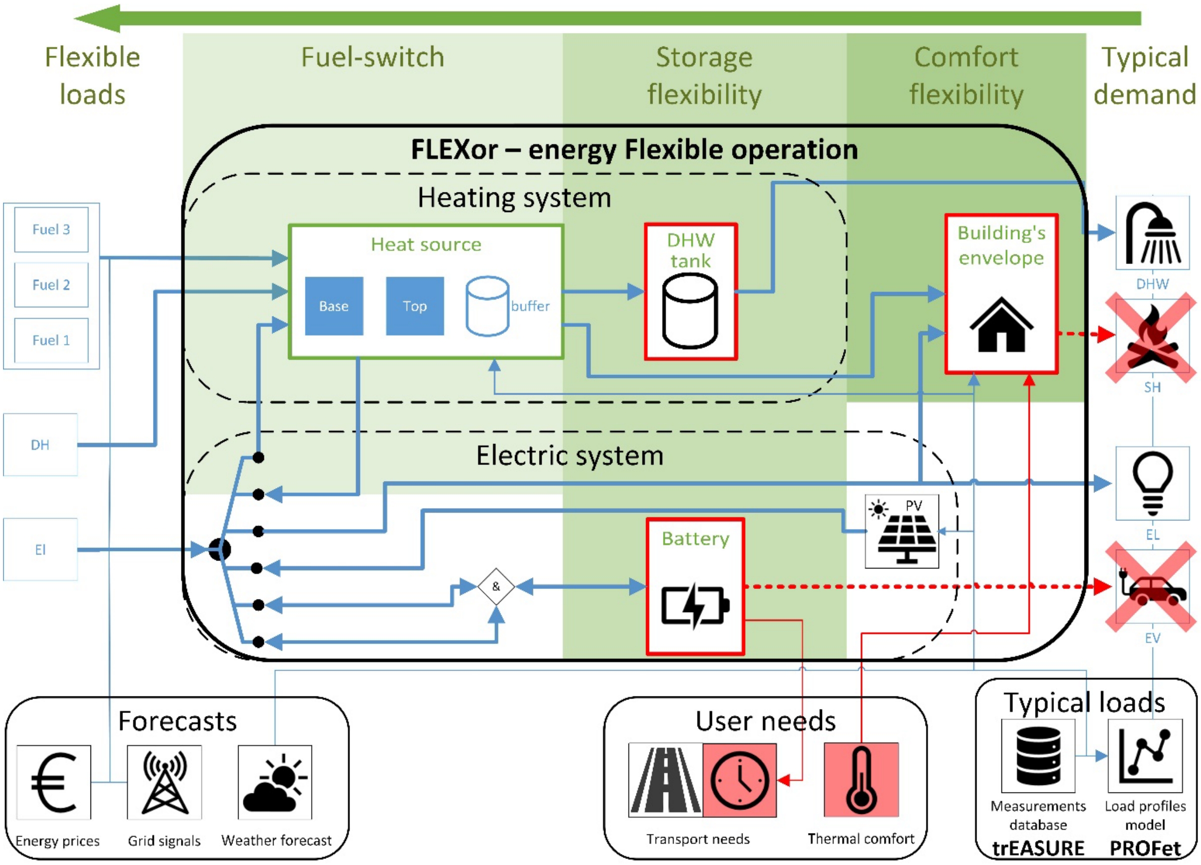

Figure 2. Schematic of the FLEXor model showing the interconnections between the modules. Thick blue lines represent energy flows, thin ones represent information flows. Red boxes highlight the flexibility sources while red lines represent the possibility to deviate from typical profiles as long as user needs are satisfied.

The first flexibility option in the schematic is called "Comfort flexibility" because it is achieved by allowing the indoor temperature to fluctuate within a predefined comfort band. In this way the thermal comfort remains satisfied while the energy use deviates from the typical demand (that is the meaning of the red cross over the icon representing the Space Heating demand). This is activated by means of charging and discharging thermal energy in the building's envelope and exploiting its slow thermal inertia. Thus, by definition, this flexibility source is available in every building.

The second flexibility option is called "Storage flexibility" because it is achieved by controlling the charge and discharge of some physical storage component, whether thermal or electric storage. One thermal storage component, the DHW tank[1], is always present, while two electric storage components are possible: Electric Vehicles (EV) and stationary Batteries. The DHW tank can be preheated, so that its energy use can follow a different profile than that of DHW demand, which is always met without

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[1] A heating system often has a buffer, represented by the tank inside the Heat source box in Figure 19, which used to allow the base unit working at its nominal conditions also at part load. However, its effect is short term and therefore already included in the hourly profile (from PROFet).

alteration. The same can be said for the electric battery, while the EV charging can be modulated but only within some constraints that safeguard the transport needs of the users.

A further flexibility option can be provided by fuel-switching, achieved by controlling the operation of the SH and DHW preparation components available in the system. Within the options currently available in the FLEXor Web app, this type of flexibility can only be activated when using the *Other* type of heat source, which is the only one that uses fuel (i.e.: neither electricity or district heating). For example, by switching to fuel consumption instead of electricity, FLEXor can reduce the peak loads and the subsequent fees related to the peak power demand.

It should be noted that all forms of flexibility come with associated energy losses.[2] For the battery this is because of inherent charge-discharge inefficiencies (the cycle losses). For the envelope and the DHW tank this is because only upward thermal flexibility is considered. This means that the temperature in the building and/or the tank is only allowed to become higher, never lower, than it is in the baseline. It is possible to preheat a building or tank, so that at a later time the energy use will be lower than in the baseline, but not the internal temperature in the module. This guarantees that the flexibility activation never comes to the detriment of user comfort. On the other hand, this causes additional heat losses and so, ultimately, a higher energy use.

2.2 Second-level model: system topology

The second-level model is where variables and balances for the energy carriers, as well as objective functions, are defined. A balance equation is declared for each energy carrier as follows:

Eq. 1 $$\boldsymbol{y_{imp}(t) - y_{exp}(t) = y_{in,HS}(t) + \left(y_{in,Batt}(t) - y_{out,Batt}(t)\right) + y_{ESP}(t) + y_{EV}(t) - y_{PV}(t)}$$

Eq. 2 $$\boldsymbol{q_{imp}(t) = q_{in,HS}(t)}$$

Eq. 3 $$\boldsymbol{fuel_{imp}(t) = fuel_{in,HS}(t)}$$

where y_{imp} and y_{exp} are electricity import and export respectively, q_{imp} is heat import from the district heating grid, $fuel_{imp}$ is import of fuel or other energy carriers; $y_{in,HS}$, $q_{in,HS}$, and $fuel_{in,HS}$ are electricity, heat and fuel input to heat-source components, respectively; $y_{in,Batt}$ and $y_{out,Batt}$ are electricity input and output in a battery; y_{ESP} is the electric-specific demand in the buildings, y_{EV} is the electric vehicle charging, and y_{PV} is electricity output from onsite PV. Depending on the system being modelled, some of these components may be inactive.

Objective functions

Baseline

The Baseline objective function is a subcase of the Energy import minimization function (see below) in which the flexibility options are restrained: no deviations from the typical energy demand profiles are allowed, energy storage is used in the typical operation mode, and the heat source components are used *base-first top-second* without any smart or optimal operation. This objective function is used for going from energy demand per service (as given by PROFet) to energy use per carrier, including all system

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[2] With the exception of EV charging, since it is only a modulation of a unidirectional flow, the EV is only charged, never discharged.

losses. It also allows to calculate the energy costs per carrier under typical operation of the building or neighbourhood.

Energy import minimization

The objective function for energy import minimization is defined as

Eq. 4 $$\min \sum_{t=0}^{T} y_{imp}(t) + q_{imp}(t) + fuel_{imp}(t) - y_{exp}(t) * f_{exp}$$

where f_{exp} is an energy export factor with a default value of 0.1. This factor is used to keep the model bounded by avoiding equal weights of import and export. Depending on the system components available, this objective can give the same results as the Baseline operation. Systems where only DH or direct electric heating are available may not allow any energy import minimization potential. The presence of heat pumps or PV (with or without battery), however, would enable the system to deviate from the Baseline operation.

Cost minimization

The objective function for cost minimization is defined as

Eq. 5 $$\min cost_{el\_grid} + cost_{dh\_grid} + cost_{energy}$$

where $cost_{el\_grid}$ and $cost_{dh\_grid}$ are the electricity and district heating grid-related costs, and $cost_{energy}$ is the cost of the energy import and export. All costs are related to the entire calculation period. Further detail on the cost calculation is given in subsection *Cost structure and calculation* under §2.3.

Flat profile

The *Flat profile*, or minimum energy import variation goal, pursues a flattening of the load profile, as much as possible while limiting the associated energy losses. Thus, the Flat profile will, at the cost of some energy loss, smoothen the “high peaks” – in a similar fashion as a Cost minimization with PPM tariff[3] – and avoid "deep valleys" and other sudden changes in the energy demand. These features might be desirable at an aggregated scale, for smooth operation of a grid and/or energy supply system. In other words, it could be said that the flat profile combines "peak shaving" and "valley filling" with respect to the typical load profile (while safeguarding comfort and user needs in the buildings). This goal is based purely on physical quantities – energy used in each hour and its variation hour by hour – and is therefore price independent. Furthermore, a slowly and mildly fluctuating load should often be desirable from the energy system perspective since it avoids steep ramp-up and ramp-down of generation units on the supply side. However, it should be noted that the flattening refers to the own energy use of each single building, without regard to what happens in other buildings or in the rest of the grid in general. In this sense it can be said that the flat profile is a building-centric optimization. The hypothesis behind the flat profile optimization is that this may be a good heuristic because peak shaving and valley filling are typically desired outcomes of energy flexible demand.

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[3] PPM = Peak Power Monthly, a type of grid tariff where the highest peak load in a month determines the power component of the grid cost for that month. Usually, PPM tariffs are designed in a way that, over a year, the power component and the energy component are approximately equally important in determining the total cost for a typical user.

The objective function for minimum energy import variation is defined as

Eq. 6 $$\min \sum_{t=0}^{T} \left(\left(y_{imp}(t) - y_{exp}(t) \right) - \left(y_{imp}(t-1) - y_{exp}(t-1) \right) \right)^{2} + \left(q_{imp}(t) - q_{imp}(t-1) \right)^{2} + \left(y_{imp}(t) + q_{imp}(t) + fuel_{imp}(t) \right) * f_{eneimp} + y_{exp}(t) * f_{eneexp}$$

where f_{eneimp} and f_{eneexp} are weighing factors on the energy import and export, respectively. These factors are needed in the model to avoid artificial energy exchanges with the grids incurred by the model as a mean to flatten the energy import profile. In addition to the objective, a limit is set on the maximum increase of energy use compared to the baseline (calculated as described above), typically at +5%.
This objective function is more computationally heavy than the other objective functions due to its quadratic terms, and it is therefore not currently available in the FLEXor Web app.

2.3 Third-level models

This subsection describes the main structure and characteristics of the third-level models in FLEXor. For further information about these models, please refer to their respective Memos, where they are described in detail.

Cost structure and calculation

The cost calculation in FLEXor is designed to allow the input of spot prices and grid-related tariffs for each energy grid: electricity and district heating. The grid tariff structure in FLEXor reflects the structures currently found in Norway, consisting of three parts:

1. Fixed tariffs: annual or monthly fees to be paid independently of the energy or power demands. A single value is given for each grid.
2. Energy related tariffs: related to the volume of energy demand. Typically, one value per season is given, but FLEXor accepts up to 12 values (i.e., one per month).
3. Power related tariffs: related to the peak power demand during each month. Typically, one value per season is given, but FLEXor accepts up to 12 values (i.e., one per month).

Since 2022, all customers in Norway, including households, are subject to power related tariffs. Spot prices are given as timeseries in the input data; it is possible to give individual price profiles for each grid. If there are grid tariffs that change throughout the day – for example, different energy related tariffs during day and night – these should be included in the timeseries profiles of spot prices. VAT should be included in the price profiles as well. All prices and tariffs should be given per kWh or kW.

PROFet

PROFet (energy demand load profile estimator) is a model that can estimate average hourly load profiles for both thermal loads (space heating (SH), heating of domestic hot water (DHW)) and electric specific loads (EL), based solely on outdoor temperatures and building area. The temperature dependency has been extracted from a database, trEASURE, of moni-tored buildings, mostly connected to district heating. Because of this, the thermal loads estimated by PROFet represent the gross heating need (*brutto varmebehov*) of a building, inclusive of all system losses. For the thermal and electric specific loads PROFet distinguishes between 11 building categories, each given with three levels of energy efficiency (Regular, Efficient, Very efficient). For an example of the models' results see Figure 3.

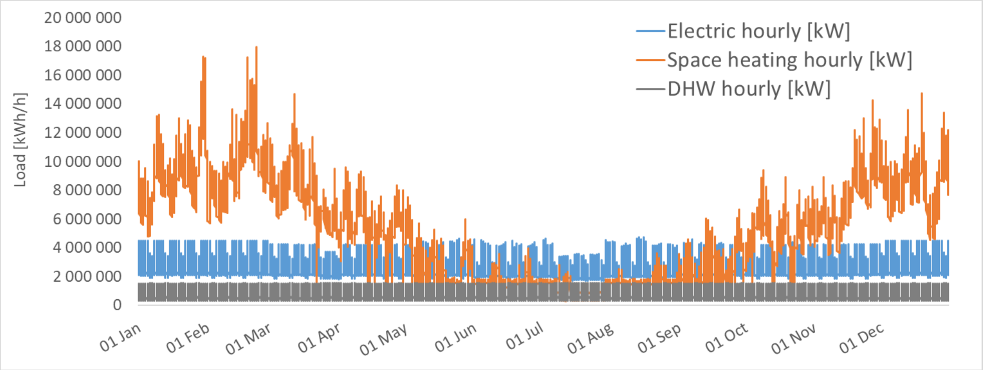

Figure 3. Load profiles generated by PROFet for the entire Norwegian building stock in 2020, using the standard reference Oslo climate from SN-NSPEK 3031 (2021).

The PROFet sub-model in FLEXor does minor preparations on the data timeseries and calls the PROFet tool itself. Its functionalities include:

- checking for holiday tags,
- asserting the units of the outdoor temperature (K or °C) and converting it to °C if needed,
- ensuring that the timeseries starts at midnight,
- resampling the timeseries to 1 hour (if needed),
- predicting the energy demand via the PROFet tool,
- resampling the energy demand back to the user given timestep if needed, and
- returning the energy demand back to the top-level model.

Generic LTI Model

Linear time invariant (LTI) systems can be described with ordinary differential equations (ODEs). These models can be formulated as continuous state space models in the following vectorial form:

Eq. 7a $$\dot{\boldsymbol{x}}(\boldsymbol{t}) = \mathbf{A}\boldsymbol{x}(\boldsymbol{t}) + \mathbf{B}\boldsymbol{u}(\boldsymbol{t}) + \mathbf{E}\boldsymbol{d}(\boldsymbol{t})$$

Eq. 7b $$\boldsymbol{y}(\boldsymbol{t}) = \mathbf{C}\boldsymbol{x}(\boldsymbol{t}) + \mathbf{D}\boldsymbol{u}(\boldsymbol{t})$$

Where $x(t)$ is the state vector, $\dot{x}(t)$ is its derivate (or next time-step value in a discrete time formulation), $u(t)$ is the input vector, $d(t)$ is the disturbance vector, such as outdoor temperature, solar gains, and internal gains, and $y(t)$ is the system's output vector.

In the domain of grey-box modelling, stochastic differential equations (SDEs) are often used to account for discrepancies between model predictions and measurements, as well as to account for noise in the measurements itself. It is also praxis to formulate the state space model using only the first set of equations (*system equations*), Eq.7a, to describe the dynamics of the system's states. While the second set of equations, Eq.7b, become static equations that relate the measurements, or observations, to the states (*observation equations*)[4]. This means that the matrix D is always null, while the matrix C contains only 0, for non-measurable states, and 1, for measurable states. Thus, $y(t)$ becomes simply the measured output vector.

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[4] Thilker, C.A., Junker, R.G., Bacher, P., Jørgensen, J.B., Madsen, H. (2021). Model Predictive Control Based on Stochastic Grey-Box Models. In: Ploix, S., Amayri, M., Bouguila, N. (eds) Towards Energy Smart Homes. Springer, Cham. https://doi.org/10.1007/978-3-030-76477-7_11

For example, in the LTI model of a building envelope, $x(t)$ would represent the temperature in the internal nodes of the building (indoor temperature, envelope structure temperature, etc. depending on the model's order), $u(t)$ would be the heat supplied by heat emitters, $d(t)$ would be the exogenous conditions affecting the building envelope, such as the outdoor temperature, solar gains and internal gains, while $y(t)$ is the measured indoor temperature.

The focus with FLEXor is to use the models within an optimization problem, to estimate the optimal response to a price signal; it is not to estimate the model's parameters from a set of measurements. This means that the system equations, Eq.7a, are described with ODEs, while the observation equations, Eq.7b, are not relevant. Furthermore, applying the "zero order hold" assumption, the continuous formulation can be transformed into discrete form:

Eq. 8 $$\boldsymbol{x}(\boldsymbol{t}+\mathbf{1}) = \mathbf{A}_{\boldsymbol{d}}\boldsymbol{x}(\boldsymbol{t}) + \mathbf{B}_{\boldsymbol{d}}\boldsymbol{u}(\boldsymbol{t}) + \mathbf{E}_{\boldsymbol{d}}\boldsymbol{d}(\boldsymbol{t})$$

The following sections show how this generic, discretised LTI model is applied to describe different components on a building (except for the Heat sources and PV that are modelled as simple input-output systems, i.e. with static, algebraic equations).

Implementation of specific LTI models

The generic LTI model is implemented in the following specific models, each described in more detail in an appendix:

- Appendix A: Building envelope
- Appendix C: Heat sources
- Appendix D: Electric vehicle charging
- Appendix E: PV system and Battery

3 Example applications

3.1 Performance calculations

A set of example cases has been defined to showcase the flexibility actions available in FLEXor. The first example focuses on the impact of the optimization objectives on the profile of imported electricity and on the indoor temperature of the building. It consists of a *regular* Apartment building with direct electric heating, no DHW tank, EV or PV system. To highlight the reaction of electricity import to spot prices, a peak power tariff is not included in this example. Figure 4 shows the electricity import profiles in three modes of operation – Baseline, Cost minimization, and Flattening – and the electricity spot price in the top plot, and the difference between the indoor temperatures in the optimized cases with respect to that of the baseline case in the bottom plot. The effect of the different operation modes is evident in the electricity import profiles. The import in the baseline operation simply follows the typical energy demand profile of a building, with two periods of high demand during daytime and low energy demand during nighttime. There is also no visual indication that this import profile reacts to the spot prices. The Cost import profile, in contrast, is highly responsive to the spot prices: there is a clear negative correlation between high prices and electricity import, which shows that the optimization seeks to reduce electricity import when prices are high aiming to reduce operation costs. And, as seen in the bottom plot, this is accomplished by increasing the indoor temperature compared to that of the baseline operation, effectively using the building as a heat storage which is “heated up” when prices are low and let to “cool down” when prices are high.

The profile of the Flattening optimization has a notably different behaviour. As the Baseline, it seems unresponsive to changes in the spot price. However, the Flattening optimization does not follow the typical energy demand profile of the building: the import profile is smoothened, instead. The bottom plot shows how the building is again used as a heat storage, yet with a different behaviour. While the Cost optimization responds to spot prices, the Flattening optimization responds to the energy demand itself, with the indoor temperature difference resembling an upside-down copy of the baseline electricity import.

The second example consists of a more complex system. It is a *regular* House with a GSHP and a direct electric heater as top heating technology, a DHW tank, one EV and a PV system. Figure 5 and Figure 6 show several profiles of the operation of the house under Cost and Flattening optimizations, respectively, with respect to the Baseline operation, during three days in June. These figures serve to exemplify how FLEXor makes use of the available components in the system in optimization processes, and how this use reflects on the electricity exchange with the grid. For example, in the Cost optimization the GSHP is used to cover all the SH and DHW demand during the shown period. This is cost efficient because of the COP of the GSHP, which is higher than the efficiency of the direct electric heater. Further, the increased use of the GSHP is assisted by the heat storages available; that is, the building mass and the DHW tank are heated up by the GSHP to store energy and thus limit the use of the direct electric heater. In contrast, the Flattening optimization makes use of the direct electric heater more than the GSHP in its attempt to flatten the export to the grid. It also increases the temperature of the building mass and of the DHW tank much more than the Cost optimization, incurring higher heat losses.

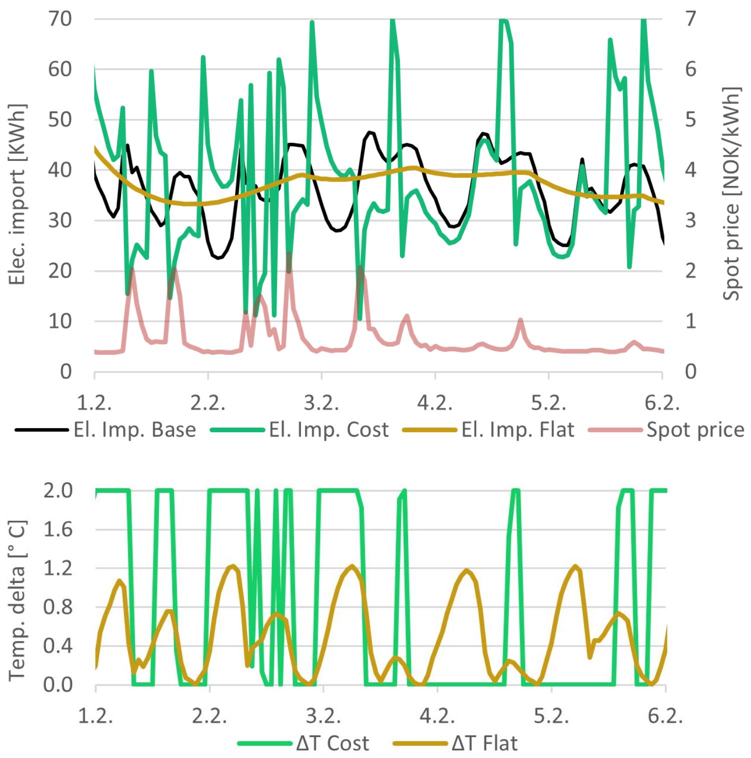


Figure 4. The electricity import profiles (top) and delta indoor temperatures with respect to the baseline (bottom) for a *regular* Apartment under Baseline operation (*Base*), Cost minimization (*Cost*) and Flattening optimization (*Flat*).

Both optimizations reduce the electricity import to the grid compared to the Baseline operation during the period shown. The Cost optimization does so because using the generation from the PV system is more cost efficient than exporting it. This is because of the grid tariffs on electricity, which are only present on imports: electricity exported, or sold, to the grid is paid at the spot price, whereas electricity imported, or bought, from the grid is charged at the spot price plus the grid tariffs. The Flattening optimization reduces the electricity import because, seeking to flatten the exchange with the grid in both directions, it stores the excess PV generation in the form of heat in the building mass and in the DHW tank, and it charges the EV with PV rather than with imported electricity.

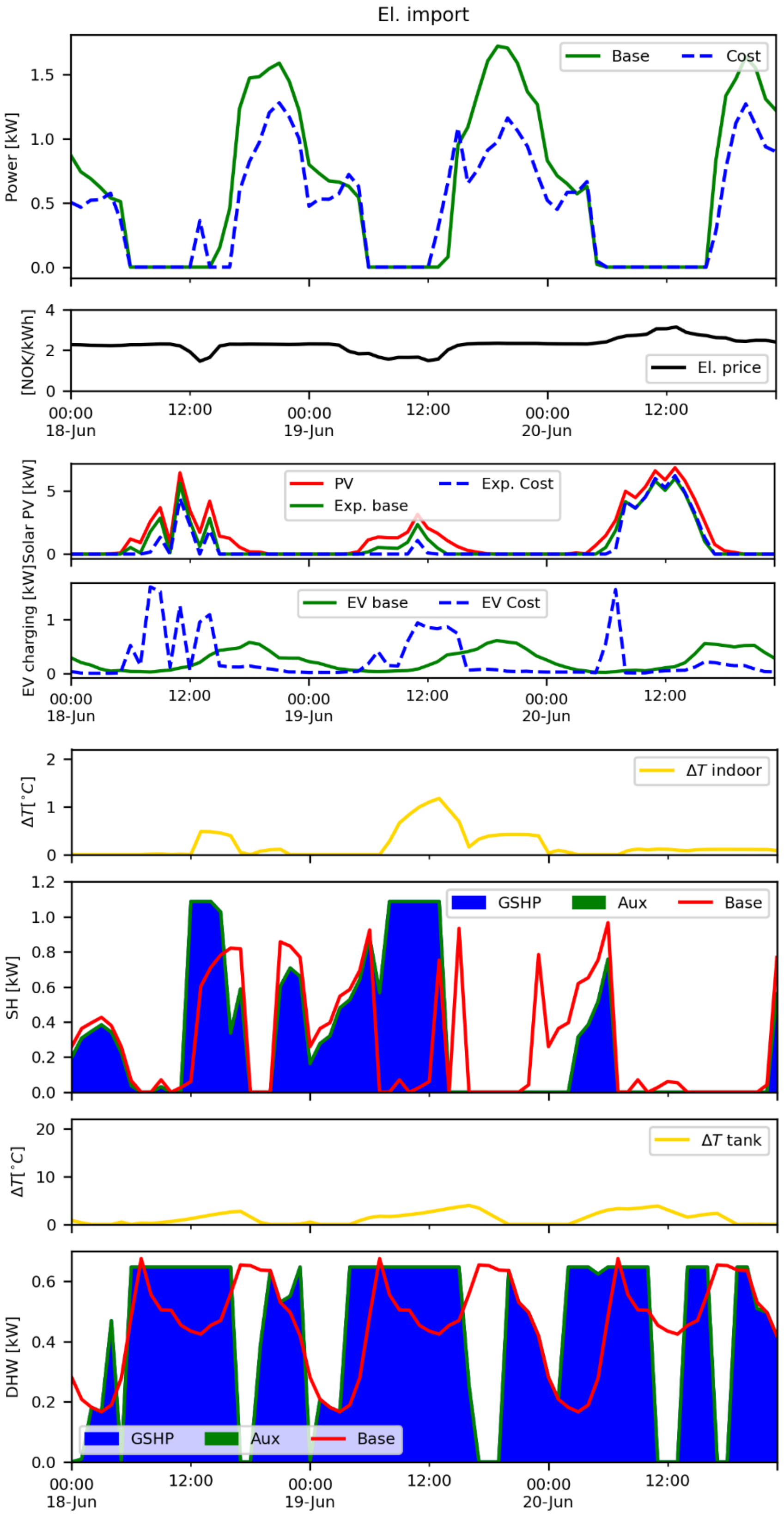


Figure 5. Selected profiles of a regular House under Baseline operation and Cost optimization.

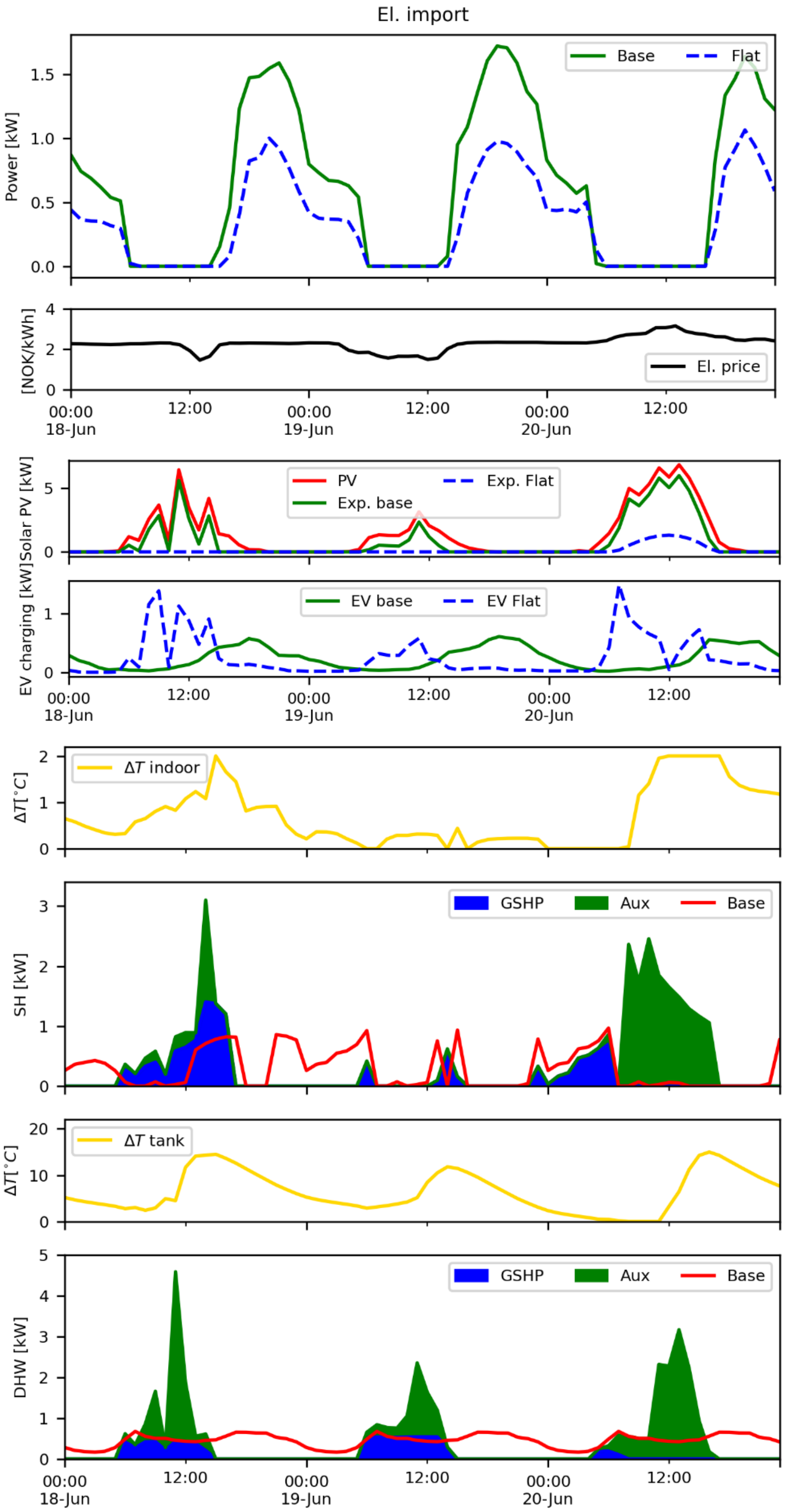


Figure 6. Selected profiles of a regular House under Baseline operation and Flattening optimization.

3.2 Potential in flexibility markets

FLEXor includes a functionality to set reference profiles of electricity import from the grid as input and to allow deviations from these profiles within user-given time windows. The aim of this functionality is to calculate the potential of space heating flexibility to shift energy demand towards (up-response) or away from (down-response) specific hours. In this subsection, an example application is presented, where space heating flexibility in an Office building is used to calculate bidding costs when participating in an intraday flexibility market.

There are some considerations to address when calculating flexibility actions within the context of a market:

- The indoor temperature must be kept at a comfortable level: space heating flexibility relies on the possibility to deviate from a reference temperature, but this deviation must remain within reasonable limits.
- Electricity import in the building must go back to "normal" values after a recovery period.
- If the building is "smart enough" to participate in a flexibility market, it is "smart enough" for flexible operation.
    - The building operation before the intraday bidding actions would be operating optimally. Therefore, it can be assumed that, for the building owner, the bidding actions are costly (as they represent a deviation from the optimal operation).
    - The cost of the space heating flexibility must be compared against optimal operation, not against typical (not optimized) operation.

To calculate the volume and cost of the flexibility actions in FLEXor, a series of steps needs to be followed. First, the baseline operation is calculated with PROFet, which represents the typical energy demand, and FLEXor calculates the energy used by the heating technologies in the buildings to cover this demand. Next, the operation of the building is optimized; in this example, the operation is optimized for cost-minimization, and thus the optimization is based on day-ahead market prices. These two profiles are shown in Figure 7.

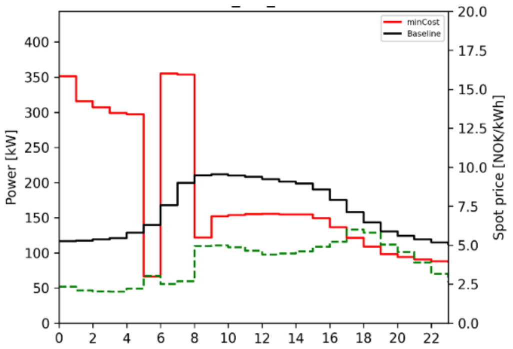
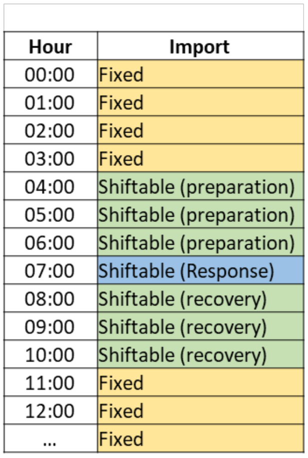


Figure 7. The baseline and cost-optimized (minCost) operations of the example building.

The next step is to define the bidding window. The bidding window has three parts. The first part is a *preparation* window: a given number of hours during which the building is free to deviate from the precalculated optimal operation, thus preparing for the bidding action. The second part is the hour(s) during which the bidding action takes place. The third part is a *recovery* window: a given number of hours during which the building is again free to deviate from the precalculated optimal operation to return to the minimum cost import profile. Outside of the bidding window, the electricity import in the building is fixed to be equal to that of the cost-optimal operation. An example bidding window is shown in Figure 8, where the bidding action is set to last one hour while the *preparation* and *recovery* windows are set to last three hours each.



Hour	Import
00:00	Fixed
01:00	Fixed
02:00	Fixed
03:00	Fixed
04:00	Shiftable (preparation)
05:00	Shiftable (preparation)
06:00	Shiftable (preparation)
07:00	Shiftable (Response)
08:00	Shiftable (recovery)
09:00	Shiftable (recovery)
10:00	Shiftable (recovery)
11:00	Fixed
12:00	Fixed
...	Fixed

Figure 8. Example of a bidding window for a 1-hour bidding event at 7:00.

Next, two separate space heating flexibility actions are calculated by shifting energy demand towards (up-response) or away from (down-response) specific hours. In up-response, the building is heated more than usual during the bidding hour(s); in down-response, the building is preheated so it can reduce its energy consumption during the bidding hour(s). These actions are calculated as cost minimizations using artificial price profiles: for down-response, the energy cost during the bidding hour(s) is only 1% of the cost during the *preparation* and *recovery* windows, whereas for up-response the energy cost during the *preparation* and *recovery* windows is 1% of the cost during the bidding hour(s). In this way, FLEXor is intended to calculate the shifting actions that shift the most energy within the comfort limits; the costs of these actions using "real" spot prices are calculated, but the model has no incentive to limit or reduce their cost. Figure 9 shows example bidding actions for down-response and up-response. In this example, the down-response deviates significantly from the minimum cost operation during the *preparation* and *recovery* windows, while the up-response doesn't require any *preparation* or *recovery*.

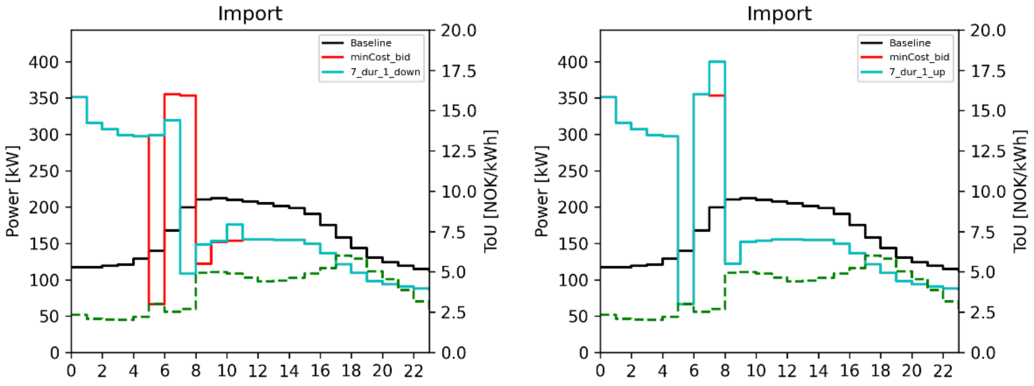


Figure 9. Down-response (left) and up-response (right) flexibility actions for bids at 7 am.

The next step is to calculate *granularity*. The maximum bids calculated in the previous steps indicate how large the deviations can be, but they may be not competitive in the market. Thus, sets of smaller bids are calculated for both the up- and down-responses. An example of granularity is shown in Table 1. The maximum up-response action calculated in the previous step was to increase the electricity import by 40 kWh at 7 am. In the granularity calculation, 4 additional fractions of that response will be calculated. A similar calculation of granularity steps is done for the down-response action.

Table 1. Example of granularity for an up-response bidding action.

minCost		Up-response	Fraction		Granular responses
kWh		kWh	%		kWh
360	+	(40	x 100%)	=	400
360	+	(40	x 80%)	=	392
360	+	(40	x 60%)	=	384
360	+	(40	x 40%)	=	376
360	+	(40	x 20%)	=	368

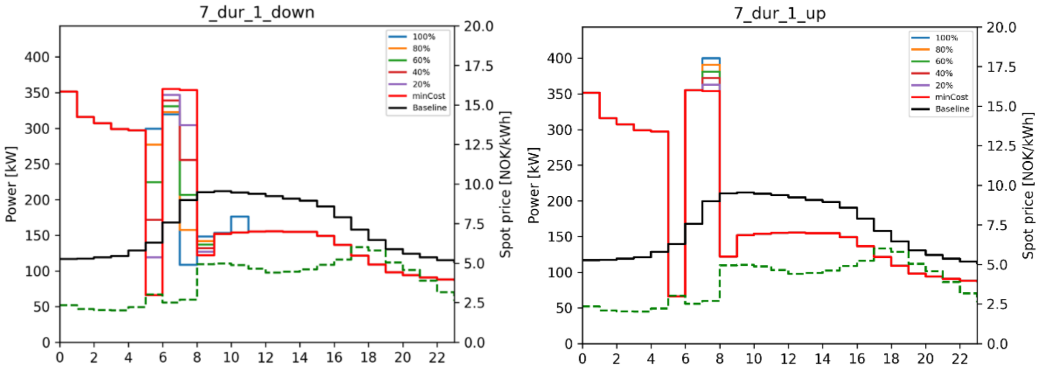


Figure 10. Example granular flexibility bidding actions during down-response (left) and up-response (right).

The electricity import by the building under the granular actions is shown in Figure 10. For the down-response the figure shows that electricity import during the *preparation* and *recovery* windows can be significantly different depending on the volume shifted in the bidding hour. This is particularly important when calculating the profitability of placing a bid, since the revenue income from the bid should be able to offset the costs incurred by deviating from the cost-optimal operation. Another advantage of calculating granularity can be deduced from Figure 11: the costs of the bidding actions may have tipping points, where increasing the volume shifted during the bidding window may be disproportionally more costly than a smaller volume. In the example shown, the maximum down-response costs roughly 200 NOK, or 0.8 NOK/kWh, whereas the 80% down-response costs 125 NOK, or 0.62 NOK/kWh.

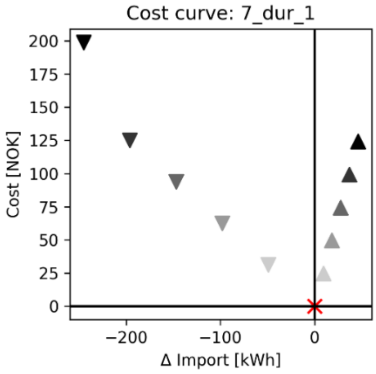


Figure 11. Cost curve of the granular bidding actions.

3.3 Energy system development

FLEXor can be used to calculate scenarios for the energy use of the building stock at large scales. An example of this application is presented here. It consists of a calculation of the energy use of the building stock towards 2040, relying on FLEXor for the energy use in the different building archetypes, and on RE-BUILDS for the development of the building stock itself. The content of this subsection is based on preliminary results from the scientific publication by S. Backe et al. (2024).

Building stock and scenarios

The building stock is divided into areas and subareas. At the top level are the five market areas in Norway – NO1 to NO5 – and the three subareas are locations with high or middle density where district heating is available (DH), and locations with low density where no thermal network is available (NTN). Finally, the buildings are differentiated by whether they have point-source heating (PS), e.g. direct electric heating, or waterborne heating (WB), e.g.: district heating. A summary of the building stock in 2020 is shown in Figure 12.

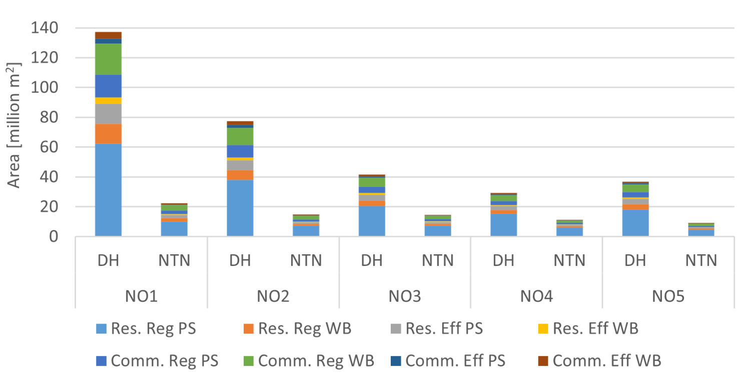


Figure 12. Summary of the Norwegian building stock in 2020 (S. Backe, 2024). Res. / Comm. = Residential / Commercial buildings; Reg / Eff = Regular / Efficient energy performance of the building's envelope.

Two scenarios for the development of the building stock have been studied. The first scenario represents a business-as-usual scenario [BAU], represents a development in which there are no measures aimed at reducing the energy demand of the building stock. In this scenario, all new construction adheres to the current energy efficiency regulations, and thus treated as efficient buildings; there are no *very efficient* buildings in this scenario. Further, only 20% of the renovated buildings are energy upgraded. This results in 80% of renovations having no impact on the energy demand. The energy efficiency scenario [En.Eff.] represents a situation where thermal insulation of the building stock is promoted. In this scenario, all new construction must adhere to passive-house standards, and thus are considered *very efficient*. Further, all the renovated buildings must be energy upgraded from *regular* to *efficient*. This leads to a reduction in the energy demand of the stock, which in turn leads to a reduction in the energy use. A summary of the development of the building stock in the two scenarios is shown in Figure 13. Detailed descriptions of the scenarios, as well as of the RE-BUILDS tool can be found in (I. Sartori et al. 2022, I. Sartori et al. 2023, N.H. Sandberg et al. 2021, N.H. Sandberg et al. 2022).

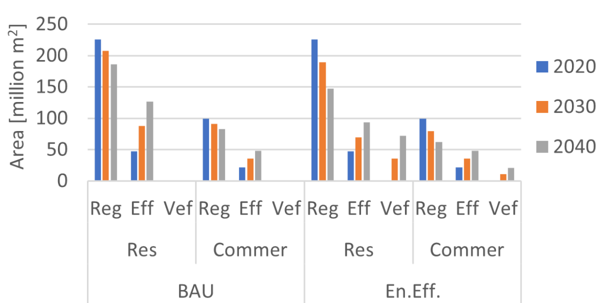


Figure 13. Summary of the development of the Norwegian building stock until 2040 under the BAU and En.Eff. scenarios (S. Backe, 2024).

Heating technologies

The heating technologies have three main characteristics which influence the energy use in the building stock: (i)how much of each technology is present in the building stock, (ii)what is the installed capacity of each technology depending on the building archetype and weather, and (iii) what is the energy efficiency of each technology. Figure 14 shows the share of heating technologies in the building stock in 2024. Some characteristics are as follows:

- Air-to-air (A2A) heat pumps can only be installed in Houses.
- Houses are not connected to district heating (DH).
- Ground-source heat pump (GSHP) is an option only in areas where there is no DH grid.

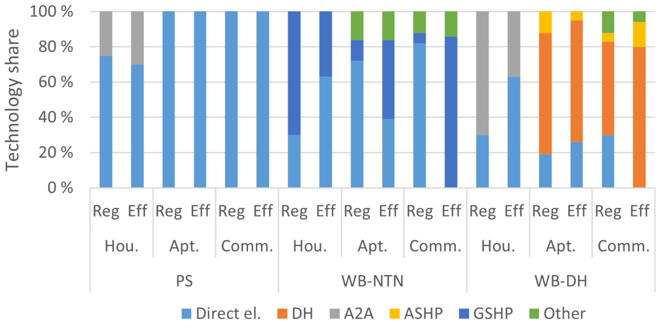


Figure 14. Shares of the heating technologies in the Norwegian building stock in 2024 (S. Backe, 2024).

In all scenarios, the technology shares in the building stock transition to a combination of DH grid, heat pumps and direct electric heating as follows:

- The share of DH remains equal to that in 2024.
- Buildings with point-source (PS) heating:
    - Houses are covered by A2A heat pumps,
    - all other are covered by direct electric heating.
- Buildings with water-borne (WB) heating: if there is DH grid and they are not covered by it, they are covered by air-to-water heat pump (ASHP); if there is no DH grid, they are covered by ground-source heat pump GSHP.
- The use of fireplaces remains the same as in 2024.
- Fossil fuel-based technologies are phased out.

These transitions reach their saturation point, or full conversion, by 2040. The installed capacities for the different heating technologies are calculated for each building archetype - building purpose and energy efficiency - and market area based on two rules:

- Heat pumps and boilers are sized at 50% of the peak space heating demand during the year.
- All other technologies are sized at sum of the peaks of space heating and domestic hot water demand during the year.

Heat pumps are always accompanied by an auxiliary, or top, electric heating component with an installed capacity equal to that of the other technologies for that building archetype and market area. The installed capacities of the heating technologies, as well as other technology components in the building archetypes, are shown in Table 2. The efficiency of the heating technologies, as well as other parameters related to their performance, are shown in the

Appendix C: Heat sources. For components other than heat pumps, their efficiency is considered to be constant. For heat pumps, in contrast, their seasonal system COP (SCOP) is related to the supply and source temperatures, calculated in accordance to the heat pump performance tables from the SN-NSPEK 3031:2021 guidelines. The top electric heating component has a constant efficiency of 99%. The use of wood in a fireplace in this study is treated differently from the other technologies. It is only available in residential buildings, and its use is related to seasons, day of the week and time of the day, and not strictly related to outdoor temperatures. The use of wood is here considered to be directly controlled by the building occupants according to the following rules:

- It is only used between September 16 and May 15.
- During weekdays it is used from 7:00 to 8:00 and from 16:00 to 23:00, and it covers 12% of the space heating demand.
- During weekends it is used from 8:00 to 23:00, and it covers 19% of the space heating demand.

Weather data

The weather data used for this study consists of EnergyPlus Weather [EPW] files for the five market areas in Norway, using a representative city for each area. The weather profiles were downloaded from Climate.OneBuilding.Org. A summary of the profiles used is shown in Table 3.

Table 2. Installed capacities of diverse technologies and number of EVs in the building archetypes.

		Hou		Apt		Commer	
DHW tank vol. [ltr]		188		960		1029	
DHW tank power [kW]		1.9		12		18.4	
Number of EVs		1		12.8		5	
PV inst. cap. [kW]		8.2		26.9		220.1	
Node	**Heating tech. inst. cap. [kW]**	**HP**	**Other**	**HP**	**Other**	**HP**	**Other**
NO1	Reg	3.5	8.4	22.5	66	81	208.8
	Eff	2	6	12.5	40.8	45	121.2
	Vef	1.5	4.8	9	32.4	31	87.6
NO2	Reg	3.5	8.4	23	66	84.5	217.2
	Eff	2	4.8	12.5	40.8	47	127.2
	Vef	1.5	4.8	9	32.4	33	93.6
NO3	Reg	3.5	8.4	23	66	82.5	212.4
	Eff	2	6	12.5	40.8	45.5	123.6
	Vef	1.5	4.8	9	32.4	31.5	90
NO4	Reg	3	8.4	21	61.2	73.5	190.8
	Eff	2	4.8	11.5	38.4	40	110.4
	Vef	1.5	3.6	8.5	31.2	27.5	79.2
NO5	Reg	3	8.4	20.5	60	70.5	183.6
	Eff	2	4.8	11	38.4	38.5	105.6
	Vef	1.5	3.6	8	30	26	76.8

Table 3. EPW weather profiles for the five Norwegian market areas.

Market area	Representative city	File
NO1	Oslo	NOR_OS_Oslo.Blindern.014920_TMYx.epw
NO2	Kristiansand	NOR_VA_Kristiansand.AP-Kjevik.014520_TMYx.epw
NO3	Trondheim	NOR_TD_Trondheim-Voll.012570_TMYx.epw
NO4	Tromsø	NOR_TR_Tromso.010260_TMYx.epw
NO5	Bergen	NOR_HO_Bergen.AP-Flesland.013110_TMYx.epw

Aggregated energy demand

The development of the energy demand of the building stock in the BAU and En.Eff. scenarios is shown in Figure 15. These results are not produced with FLEXor, but rather a combination of PROFet data and the PV module; nevertheless, they are necessary for the correct interpretation of the results from FLEXor. The figure shows that the En.Eff. reduces the energy demand in 2040 by over 5 TWh, with nearly all those savings coming from a lower space heating demand. Nevertheless, the figure also shows that the energy efficiency measures in the mass of the building stock do not lead to a reduction in energy demand compared to 2020, indicating that the energy saving measures are not enough to offset the demand increase caused by the growth of the building stock.

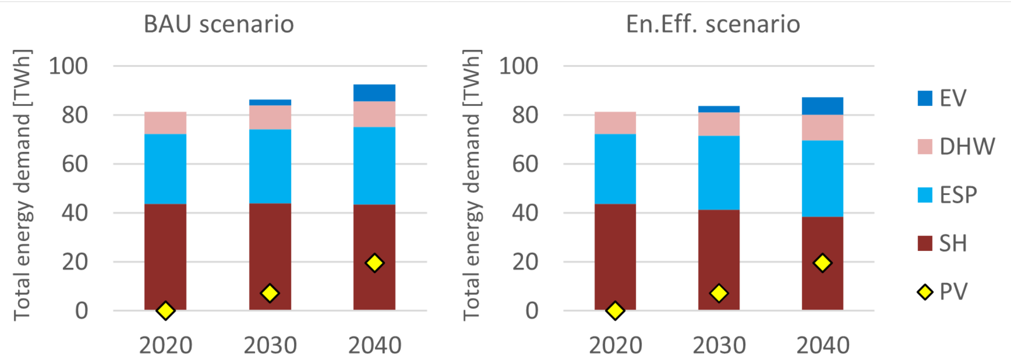


Figure 15. Development of the energy demand of the building stock in the BAU and En.Eff. scenarios (S. Backe, 2024). EV= Electric Vehicle; DHW= Domestic Hot Water tank; ESP= Electric Specific (unflexible); SH= Space Heating; PV= solar Photovoltaic.

Energy use

The development of the energy exchange with the grids by the Norwegian stock by scenario and heuristic is shown in Figure 16; the top plots show the development of the net electricity import, while the bottom plots show the import from the district heating grid. The net electricity import is significantly reduced in both scenarios and with all heuristics in 2040 compared to 2020. This is mostly due to the ambitious technology upgrade, where the best available technologies (heat pumps) reach high penetration in the building stock by 2040. The import of heat from the DH grid is not affected by the improvement of the SH technologies in the building stock, and thus it increases until 2040 due to the growth of the energy demand shown in Figure 15.

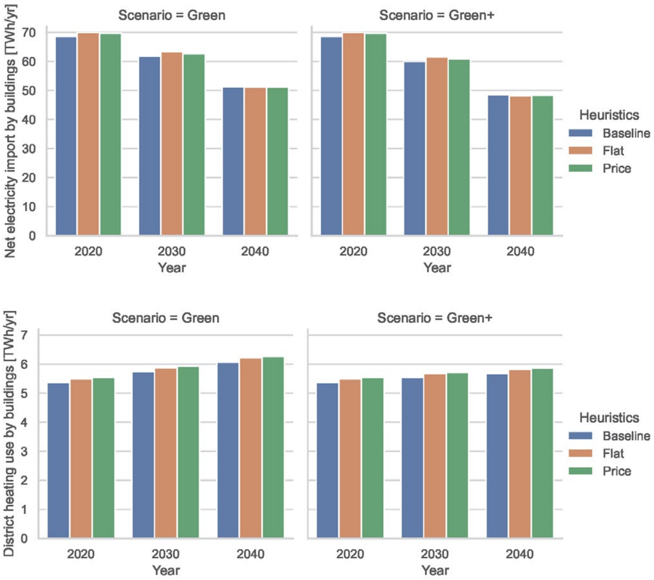


Figure 16. Development of the net electricity import (top) and district heating use (bottom) in the Norwegian building stock by scenario and heuristic (S. Backe, 2024).

Figure 17 shows the energy use and PV curtailment in 2040 in the Norwegian building stock by scenario and heuristic. PV curtailment is calculated under the assumption that generation from onsite PV systems can be shared among buildings but not with other users (such as industry), and it cannot be exported to market areas within or without Norway. These plots show more explicitly the differences between the heuristics. Notably, they show significant curtailment of PV in the Baseline and Price heuristics, whereas the Flat heuristic avoids most curtailment by increasing the self-consumption of PV generation onsite. The figure highlights, however, that the Flat heuristic increases the total energy use in the building stock compared to both the Baseline and the Price heuristics.

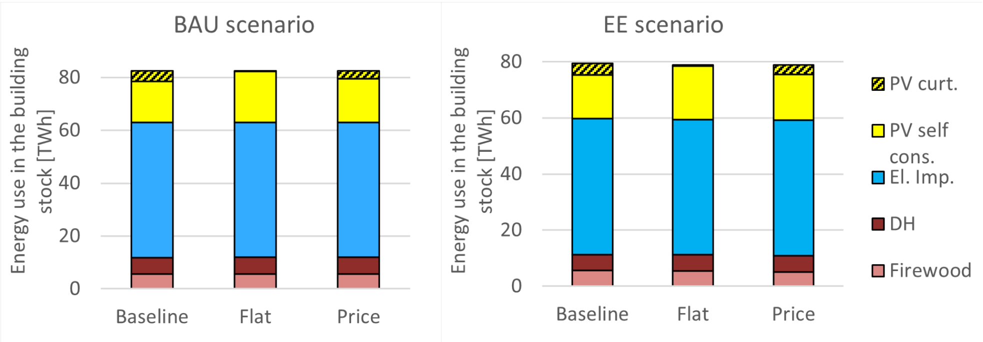


Figure 17. Energy use and PV curtailment in the Norwegian building stock in 2040 by scenario and heuristic.

ZEN KPIs

An example calculation of the ZEN flexibility KPIs for the Norwegian building stock in 2040 as calculated with FLEXor are shown in Figure 18; the top plots show the absolute values of the ZEN KPIs, while the bottom plots show the difference with respect to the Baseline heuristic as percentages. Further information about the ZEN KPIs, their purpose and calculations can be found in [M.K. Wiik et al. 2024].

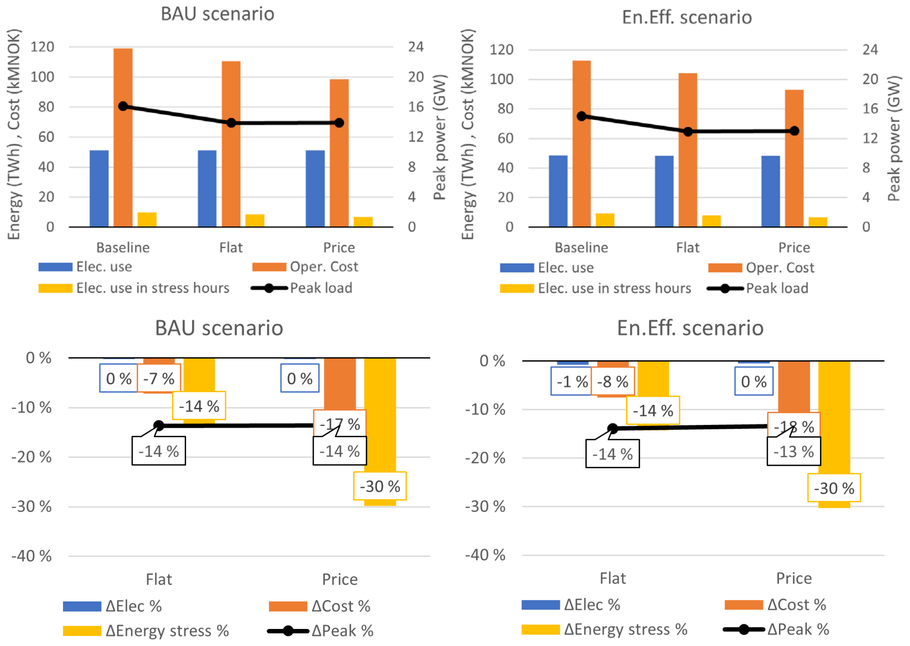


Figure 18. ZEN KPIs for the Norwegian stock in 2040 in absolute value (top) and as percentage relative to the Baseline heuristic (bottom) by scenario and heuristic.

4 Web application and archetype buildings

The FLEXor calculation engine is available online. It allows to perform energy flexibility optimizations for one building archetype and one month at a time with the *Baseline*, *Energy import minimization* or *Cost minimization* objectives. The FLEXor calculation engine, or backend, resides on a SINTEF server and can be accessed through a frontend via two entry points (or interfaces). The first entry point is an Excel file, in which the end-user can select the building archetype, activate or deactivate space heating and other sources of flexibility, and modify some of the input parameters to the model. Upon making changes to these characteristics, the Excel file automatically adapts any other parameters as needed. This entry point has been created to allow a wider audience to use FLEXor, given the extended presence and large user-base of Excel. Upon loading the Excel file to the Web application, it is sent to an API which interacts with the FLEXor calculation engine. The second entry point is directly through the API and is intended for expert users or use by other software, using json files for input and output. Figure 19 shows a schematic representation of the access points and internal communications when using the FLEXor calculation engine.

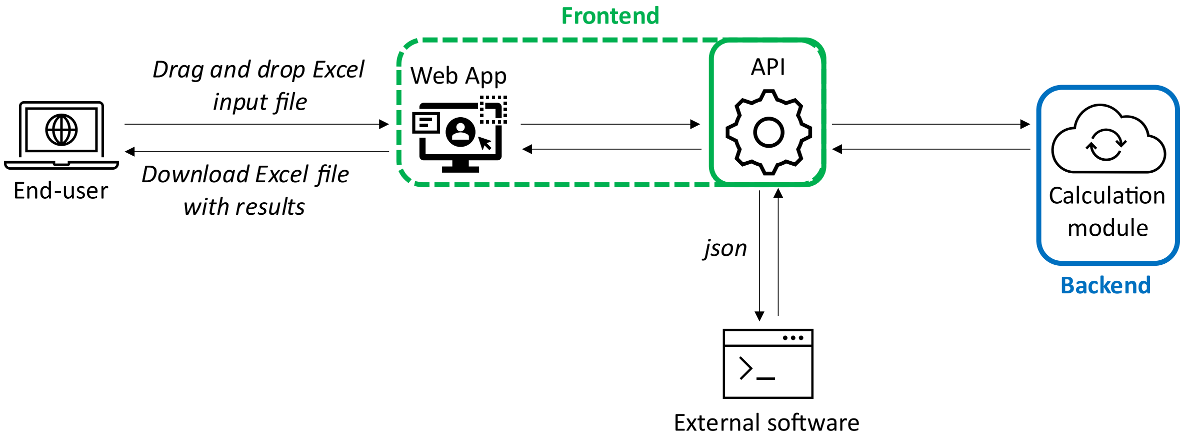


Figure 19. Access points and internal communications between end users and/or external software with FLEXor.

When using the Excel file, some inputs must are required (in dark yellow cells), some inputs may be changed (in blue cells), and defaults values (in green cells) are given for the inputs that may be changed. The inputs that are required from the end-user are as follows:

- Building type (House, Apartment, Commercial) and efficiency (Regular, Efficient, Very efficient).
- Flexible space heating (Yes/No).
- Month to be calculated
- Objective of the optimization (Baseline, Energy import minimization or Cost minimization)
- Availability of PV (Yes/No).
- Availability of Battery (Yes/No). Note: if PV is not available, the battery will not be included in the model regardless of user input.
- Availability of EV (Yes/No).
- Flexible charging of EV (Yes/No).
- Type of base heating component (Electric heater, ground-source heat pump, air-source heat pump, air-to-air heat pump, district heating, other).
- Availability of Firewood heater (Yes/No). Note: only available for House and Apartment.
- Flexible charging of domestic hot water tank (Yes/No).

The characteristics of the building archetypes available in the Excel file are shown in

Appendix F: Characteristics of archetypes and main parameters in the FLEXor Web application. Some input parameters may be changed by the user, such as building area, energy costs, and presence and characteristics of some of the energy components. If the user does not give any values for these parameters, the default values are used. These defaults values can also be found in. The user should be aware that some input parameters are interdependent; therefore, changing some parameters may cause other parameters to be automatically updated. All the default values that required pre-calculations of the building operation were obtained using the NS3031:2014 standard climate data. Expert users will have access to an extensive list of parameters that can be adjusted: their description and interrelations are beyond the scope of this report.

The FLEXor and PROFet Web applications can be accessed through the following links:

- PROFet Web app: https://profet.jollymeadow-8539f348.norwayeast.azurecontainerapps.io/
- FLEXor Web app: https://flexor.jollymeadow-8539f348.norwayeast.azurecontainerapps.io/
- API for both: https://flexibilitysuite.byggforsk.no/index.html

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SN-NSPEK 3031 (2021) Bygningers energiytelse — Beregning av energibehov og energiforsyning, *Standard Norge Norsk Spesifikasjon*.

Appendix A: Building envelope

The building envelope is modelled as an indoor and envelope temperatures *TiTe* model, see **Error! Reference source not found.**. *TiTe* is a two-state formulation where, in addition to the indoor temperature, the internal temperature of the building envelope is calculated. The model is designed to consider q_{sh} as the input and the following inputs as disturbances: outdoor temperature T_{out}, global horizontal solar radiation I_s, internal gains q_{int} and ventilation heat q_{vent}. If any of these disturbances should be neglected, their input time series are set to zero. I_s is multiplied by the parameter gA_w which represents the effective window area multiplied with its g-value. Moreover, the solar radiation, internal gains and ventilation heat are multiplied by the factors α_s, α_i and α_v, respectively. Further details about these factors are given in Section **Error! Reference source not found.**. The model can be represented by the following RC-network:

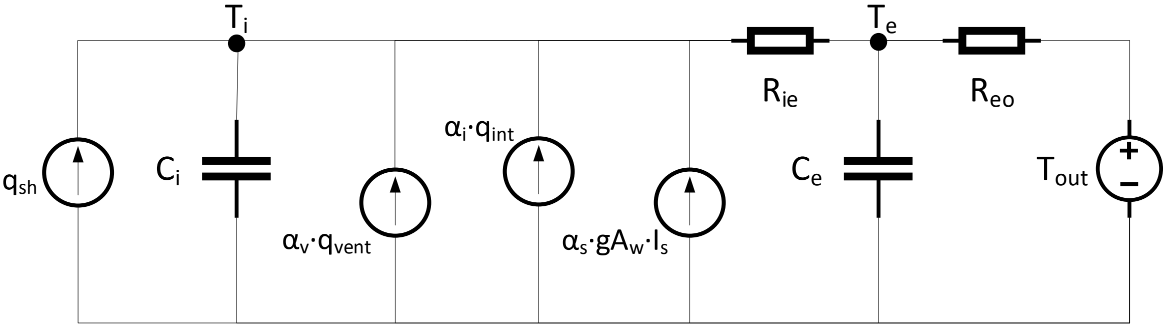

Figure 20. RC-circuit representation of the second order *TiTe* model (B. Manrique Delgado et al., 2024).

And the following differential equations:

Eq. 9 $$dT_i = \frac{1}{C_i R_{ie}}(T_e - T_i)dt + \frac{1}{C_i}(q_{sh} + \alpha_s * gA_w * I_s + \alpha_i * q_{int} + \alpha_v * q_{vent})dt$$

Eq. 10 $$dT_e = \frac{1}{C_e R_{ie}}(T_i - T_e)dt + \frac{1}{C_e R_{eo}}(T_{out} - T_e)dt$$

where:

States	
T_i	Indoor temperature
T_e	Internal temperature of the building envelope
Parameters	
C_i	Thermal capacity of interior
C_e	Thermal capacity of building envelope
R_{ie}	Thermal resistance between indoor and envelope state
R_{eo}	Thermal resistance between envelope state and outdoor
gAw	Effective window area

As described above, the system can be represented by a continuous state model with Eq. 7a where:

$$\boldsymbol{x}(\boldsymbol{t}) = \begin{bmatrix} \boldsymbol{T_i}(\boldsymbol{t}) \\ \boldsymbol{T_e}(\boldsymbol{t}) \end{bmatrix}, \qquad \boldsymbol{u}(\boldsymbol{t}) = [\boldsymbol{q_{sh}}], \qquad \boldsymbol{d}(\boldsymbol{t}) = \begin{bmatrix} \boldsymbol{T_{out}} \\ \boldsymbol{I_s} \\ \boldsymbol{q_{int}} \\ \boldsymbol{q_{vent}} \end{bmatrix},$$

$$\mathbf{A} = \begin{bmatrix} -\frac{1}{C_i R_{ie}} & \frac{1}{C_i R_{ie}} \\ \frac{1}{C_e R_{ie}} & -\frac{1}{C_e (R_{ie} + R_{eo})} \end{bmatrix}, \qquad \mathbf{B} = \begin{bmatrix} \frac{1}{C_i} \\ \mathbf{0} \end{bmatrix}, \qquad \mathbf{E} = \begin{bmatrix} \mathbf{0} & \frac{\alpha_s * \mathbf{gAw}}{C_i} & \frac{\alpha_i}{C_i} & \frac{\alpha_v}{C_i} \\ \frac{1}{C_e R_{eo}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}.$$

A set of nine archetypes has been developed, consisting of three types of building – *House*, *Apartment*, and *Commercial* – at three energy efficiency levels – *Regular*, *Efficient*, *Very Efficient*. The *House* archetype represents detached and semi-detached houses containing 1.25 dwellings; *Apartment* represents an apartment building with 16 dwellings; and *Commercial* represents a building used for commercial purposes. It is meant to be considered an amalgamation of several types of commercial buildings such as offices, schools, shops, etc., created as a weighted average of the accumulated floor area in the building stock for these types of buildings.

The efficiency levels represent three categories of heat demand required by the buildings: *Regular* represents a building with energy demand representative of an average of the building stock, *Efficient* represents buildings from 2010 and later adhering to current energy efficiency guidelines, and *Very Efficient* represents buildings with energy demand similar to buildings adhering to a *Passive house* standard. Each combination of building type and efficiency level has a set of RC values for their representation as RC models. Further details on the PV system models can be found in ZEN Memo: Building Envelope Modelling (B. Manrique Delgado et al, 2024).

Appendix B: Hot water tank

The hot water tank model is based on the system shown in Figure 21, which shows a DHW tank in steady state, with an internal state, heat supply from a heating element q_{in}, heat output q_{out} by delivering hot water and receiving cold water, and heat losses q_{loss}. Three temperatures are shown inside the tank; T_{mix} represents the average temperature inside the tank, while T_{top} and T_{bottom} represent the maximum and minimum allowed temperatures, T_{max} and T_{min}, respectively.

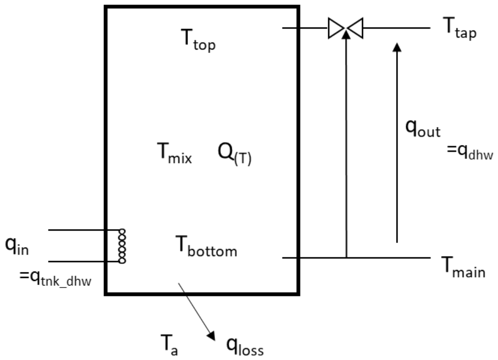

Figure 21. DHW tank in steady state (B. Manrique Delgado et al, 2022a).

The heat content of the tank Q at temperature T can be calculated as

Eq. 11 $$Q(T) = V * \rho * c_p(T - T_{ref})$$

where V is the tank volume, ρ is the density of water, c_p is the specific heat capacity of water at constant pressure, and $T_{ref}$is the reference temperature. For this system, the reference temperature is

$T_{ref} = T_a$ and $Q(T_a) = 0$

The balance equation for the system is calculated as

Eq. 12 $$\Delta Q = (q_{in} - q_{out} - q_{loss})\Delta t$$

where the losses are calculated as

Eq. 13 $$q_{loss}(T) = \frac{1}{R_t}(T - T_a)$$

and R_t is the thermal resistance of the tank.

The Input-State-Output model for the tank consists of a single-state space model for the internal temperature of the tank T_{int}, similar to T_{mix} mentioned above. We can define the thermal capacitance of the tank C_t as

Eq. 14 $$C_t = V * \rho * c_p$$

And the energy balance in the tank can be formulated for T_{int} as

Eq. 15 $$\frac{dT_{int}}{dt} = -\frac{1}{C_t R_t}(T_{int} - T_a) + \frac{1}{C_t} * q_{in} - \frac{1}{C_t} * q_{out}$$

The system can be represented by a continuous state model with Eq. 7a where

$$\boldsymbol{x}(\boldsymbol{t}) = [\boldsymbol{T}_{\boldsymbol{int}}(\boldsymbol{t})], \qquad \boldsymbol{u}(\boldsymbol{t}) = [\boldsymbol{q}_{\boldsymbol{in}}], \qquad \boldsymbol{d}(\boldsymbol{t}) = \begin{bmatrix} \boldsymbol{q}_{\boldsymbol{out}} \\ \boldsymbol{T}_{\boldsymbol{a}} \end{bmatrix},$$

$$\mathbf{A} = \left[-\frac{\mathbf{1}}{\boldsymbol{C}_{\boldsymbol{t}}\boldsymbol{R}_{\boldsymbol{t}}}\right], \qquad \mathbf{B} = \left[\frac{\mathbf{1}}{\boldsymbol{C}_{\boldsymbol{t}}}\right], \qquad \mathbf{E} = \left[-\frac{\mathbf{1}}{\boldsymbol{C}_{\boldsymbol{t}}} \quad \frac{\mathbf{1}}{\boldsymbol{C}_{\boldsymbol{t}}\boldsymbol{R}_{\boldsymbol{t}}}\right]$$

Further details on the hot water tank model can be found in ZEN Memo 42: DHW Tank Modelling (B. Manrique Delgado et al, 2022a).

Appendix C: Heat sources

The heat pump model, at its core is a simple calculation as shown in the equation below where y_{in} is the electricity input to heat pump and q_{SH} and q_{DHW} are the heat output from the heat pump intended for space heating and for DHW heating, respectively, and COP_{SH} and COP_{DHW} are the coefficients of performance of the heat pump for supplying heat intended space heating and for DHW heating, respectively. The operation of the heat pump is constrained by the conditions given below, where $Q_{HP,SH}$, $Q_{HP,DHW}$, and Q_{HP} are the heat pump capacities for delivering heat intended for space heating, for DHW heating, and in total, respectively. The two sub-models – constant performance model and temperature-dependent model – mainly differ in how COP_{SH}, COP_{DHW}, $Q_{HP,SH}$ and $Q_{HP,DHW}$ are calculated.

Eq. 16a $$y_{in}(t) = \frac{q_{SH}(t)}{COP_{SH}(t)} + \frac{q_{DHW}(t)}{COP_{DHW}(t)}$$

subject to the constraints

Eq. 16b $$q_{SH}(t) \leq Q_{HP,SH}(t)$$

Eq. 16c $$q_{DHW}(t) \leq Q_{HP,DHW}(t)$$

Eq. 16d $$q_{SH}(t) + q_{DHW}(t) \leq Q_{HP}(t)$$

Constant performance model

The constant performance model requires only three input parameters: the installed capacity of the heat pump Q_{HP}, a nominal COP for space heating, and a nominal COP for DHW heating. In this model, none of the COPs nor the heat pump capacities are temperature dependent. COP_{SH} and COP_{DHW} are constant values given by the user, whereas the heat pump capacities are calculated based on the following equation, which simply states that the total heat output of the heat pump cannot exceed its installed capacity.

Eq. 17 $$Q_{HP,SH}(t) + Q_{HP,DHW}(t) \leq Q_{HP}$$

All heat sources different to heat pumps (i.e. direct electric heaters, boilers, district heating) are modelled as constant performance models in which the energy carrier can be electricity, heat from district heating, or fuel.

Temperature-dependent performance

The temperature-dependent model requires the three input parameters given in the constant performance model – installed capacity and two nominal COPs – plus three more: temperature of the heat source, supply temperature for space heating, and supply temperature for DHW preparation. The model uses performance tables for heat pumps from the Norwegian Standard SN-NSPEK 3031:2021 for the calculation of buildings' energy performance. The tables for the calculation of GSHP, ASHP, and A2A heat pumps are shown in Table 4. For each timestep during the optimization, both the heat delivery capacities and the COPs for space heating and for DHW heating are calculated by multiplying the installed capacity of the heat pump by the factors interpolated based on the table. There are two considerations with regards to the A2A heat pump. First, this type of heat pump cannot deliver heat for DHW heating. Second, the supply temperature is assumed to be a constant value of 20° C.

Two optional input parameters can be given: the maximum coverage factor for space heating and the maximum coverage factor for DHW heating. These parameters can be used to specify a limit on the contribution of heat by the heat pump to the total demand for space heating or DHW heating. This limit is set and valid for each timestep, not for the sum of the heat demand during the calculation interval.

Table 4: Table for the calculation of heat delivery capacity and COP for GSHP, ASHP and A2A heat pumps (B. Manrique Delgado et al, 2023), based on SN-NSPEK 3031:2021.

		Q_{HP}			COP		
		T_{sou}			T_{sou}		
	T_{sup}	**-5**	**0**	**5**	**-5**	**0**	**5**
GSHP	35	0.92	1	1.15	0.78	1	1.1
	55	0.82	0.91	1	0.43	0.58	0.73
	T_{sup}	**-15**	**2**	**7**	**-15**	**2**	**7**
ASHP	35	0.55	0.73	1	0.48	0.71	1
	55	0.44	0.65	0.89	0.32	0.45	0.68
	T_{sup}	**-15**	**2**	**7**	**-15**	**2**	**7**
A2A	20	0.54	0.79	1	0.62	0.72	1

Further details on the heat source models can be found in ZEN Memo 49: Heat Pump, Solar PV and Battery Systems Modelling (B. Manrique Delgado et al, 2023).

Appendix D: Electric vehicle charging

The EV models are similar to that of a battery in that EVs can be charged and discharged. However, the focus of the model presented here is on the charging demand, not stored energy. This is because the available data does not provide information about the total energy stored in the battery of the EV, nor of its State-of-Charge (SOC): it only shows how much energy needs to be charged. Stationary losses are not included.

The state space model for the EV consists of one internal state – the charging demand $\boldsymbol{Y_{ch\,demand}}$ – and one input and one output – charging power $\boldsymbol{y_{charge}}$ and discharging power $\boldsymbol{y_{discharge}}$. The balance equation for the charging demand can be calculated as

Eq. 18 $$\Delta \boldsymbol{Y_{ch\,demand}(t)} = \left(\boldsymbol{y_{discharge}(t)} - \boldsymbol{y_{charge}(t)} * \boldsymbol{\eta_{ch}}\right)\Delta \boldsymbol{t}$$

where $\boldsymbol{\eta_{ch}}$ is charging efficiency. While EVs also have discharging efficiency, this model assumes it is included implicitly in $\boldsymbol{y_{discharge}}$. To calculate the dynamics of the system, the equation above can be written as

Eq. 19 $$\frac{\boldsymbol{Y_{ch\,demand}(t+1)} - \boldsymbol{Y_{ch\,demand}(t)}}{\Delta \boldsymbol{t}} = \boldsymbol{y_{discharge}(t)} - \boldsymbol{y_{charge}(t)} * \boldsymbol{\eta_{ch}}$$

In the available data the EV discharge is given as energy, not power. Therefore, the discharging power is replaced by discharged energy $\boldsymbol{Y_{discharge}}$. The equation can be rewritten as

Eq. 20 $$\boldsymbol{Y_{ch\,demand}(t+1)} = \boldsymbol{Y_{ch\,demand}(t)} + \boldsymbol{Y_{discharge}(t)} - \boldsymbol{y_{charge}} * \boldsymbol{\eta_{ch}} * \Delta \boldsymbol{t}$$

The system can be represented by a discrete state space model with Eq. 8 where

$$\boldsymbol{x(t)} = [\boldsymbol{Y_{ch\,demand}(t)}], \qquad \boldsymbol{u(t)} = \begin{bmatrix} \boldsymbol{Y_{discharge}} \\ \boldsymbol{y_{charge}} \end{bmatrix}, \qquad \boldsymbol{d(t)} = [\,],$$

$$\mathbf{A}_{\boldsymbol{d}} = [\mathbf{1}], \qquad \mathbf{B}_{\boldsymbol{d}} = [\mathbf{1} \quad -\boldsymbol{\eta_{ch}} * \Delta \boldsymbol{t}], \qquad \mathbf{E}_{\boldsymbol{d}} = [\,],$$

Further details on the EV model can be found in ZEN Memo 43, and the data used here as input for it are taken from measurement campaigns over prolonged periods that collected data from tens of thousands of charging sessions from several locations in Norway (Sørensen *et al.* 2021, 2023).
Figure 22 shows the typical charging profiles and average connected capacity per EV unit. In the case of Residential buildings (House and Apartments) the EV unit is a single user (or car), while for Commercial buildings the EV unit is a single charging point.

The charging profile is the average of the measurements, per EV unit, and is divided into inflexible, for the charging events that did not have at least one idle hour during the time the car was connected, and flexible, for all the others. The connected capacity indicates how much charging capacity is available, per EV unit, in average for every hour. The difference between the average connected capacity and the average charging profile expresses how much flexibility the EV unit has to offer. Therefore, in Residential buildings the flexibility potential is highest at night while in Commercial buildings it is highest in daytime. Further details on the EV model can be found in ZEN Memo 43: Electric Vehicle Modelling (B. Manrique Delgado et al, 2022b).

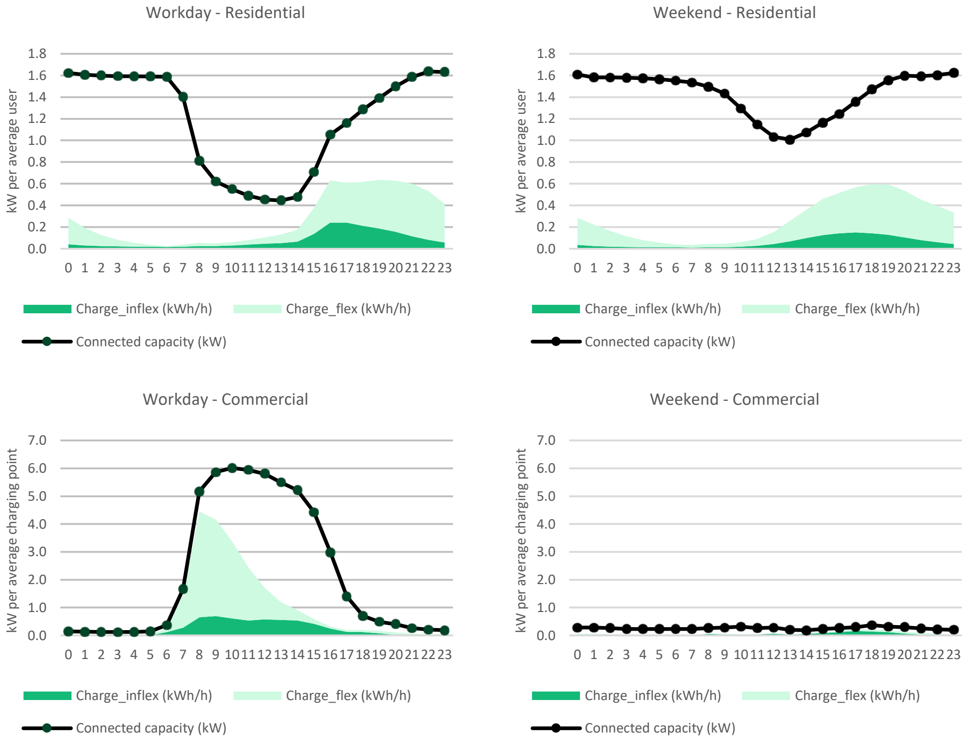

Figure 22. Electric Vehicle (EV) typical charging profiles and connected capacity in Residential (*top*) and Commercial (*bottom*) buildings; for average workdays (*left*) and weekend days (*right*) (B. Manrique Delgado et al, 2022b).

Appendix E: PV system and Battery

PV system

Two models for PV generation have been implemented, giving users the option to supply pre-calculated time-series (or profiles) of electricity generation, or to let the model calculate the time-series. The first option, named specific production model, gives the user more freedom to test different PV generation scenarios, as they have the option to modify the generation profiles to fit specific needs. For example, the user can give specific production profiles that correspond to years with very high or very low annual generation, focus on peak days or weeks, or even implement unique situations, such as sudden drops or increases in generation.

The second option, instead, named calculation model, uses the Global Solar Energy Estimator (GSEE) (Stefan et al., 2016) library to calculate the electricity output from a PV system. This model requires other input data and parameters than what is required in the specific production model. Namely, the user must specify the geographical coordinates (latitude and longitude), panel tilt, azimuth, tracking and installed capacity, and give time-series of outdoor temperature, global horizontal radiation in $\mathrm{W/m_2}$, and either diffuse horizontal radiation in $\mathrm{W/m^2}$ or the fraction of global horizontal radiation that corresponds to diffuse radiation. Further details on the PV system models can be found in ZEN Memo 49: Heat Pump, Solar PV and Battery Systems Modelling (B. Manrique Delgado et al, 2023).

Electric battery

The state space model of the battery consists of one internal state – the state-of-charge (SoC) of the battery $\boldsymbol{Y_{SoC}}$ – and one input and one output – charging power $\boldsymbol{y_{charge}}$ and discharging power $\boldsymbol{y_{discharge}}$. The balance equation of the battery is

Eq. 21
$$\boldsymbol{Y_{SOC}(t+1) = Y_{SoC}(t) + \frac{y_{charge}(t)}{\eta_{charge} * CAP}\Delta t + \frac{y_{discharge}(t)}{\eta_{discharge} * CAP}\Delta t}$$

where η_{charge} and $\eta_{discharge}$ are the charging and discharging efficiencies, respectively, CAP is the battery capacity, and Δt is the model timestep. The system can be represented with Eq. 8 where

$$\boldsymbol{x(t)} = [\boldsymbol{Y_{SOC}(t)}], \qquad \boldsymbol{u(t)} = [\boldsymbol{y_{charge}} \quad \boldsymbol{y_{discharge}}], \qquad \boldsymbol{d(t)} = [\,],$$

$$\mathbf{A}_{\boldsymbol{d}} = [\mathbf{1}], \qquad \mathbf{B}_{\boldsymbol{d}} = \left[\frac{\boldsymbol{\eta_{charge} * \Delta t}}{\boldsymbol{CAP}} \quad -\frac{\boldsymbol{\Delta t}}{\boldsymbol{\eta_{discharge} * CAP}}\right], \qquad \mathbf{E}_{\boldsymbol{d}} = [\,].$$

where *x(t)* represents the state vector, and *u(t)* the input vector. The model is also ruled by the constraints shown below, where $Y_{SoC,min}$ and $Y_{SoC,max}$ are the minimum and maximum SoC set to zero and one by default, and y_{max} is the maximum charging and discharging rate.

Eq. 22a
$$\boldsymbol{Y_{SoC,min} \leq Y_{SoC}(\mathbf{t}) \leq Y_{SoC,max}}$$

Eq. 22b
$$\boldsymbol{y_{charge} \leq y_{max}}$$

Eq. 22c
$$\boldsymbol{y_{discharge} \leq y_{max}}$$

Further details on the electric battery models can be found in ZEN Memo 49: Heat Pump, Solar PV and Battery Systems Modelling (B. Manrique Delgado et al, 2023).

Appendix F: Characteristics of archetypes and main parameters in the FLEXor Web application

Table 5. Geometric characteristics of the building archetypes.

	House	Apartment	Commercial
Floor area (BRA) per building [m^2]	150	1120	3600
Floor area (BRA) per dwelling [m^2]	120	70	0
Dwellings per building [#]	1.25	16	0
Nr. floors [#]	2.14	4.16	1.63
Ceiling height [m]	2.4	2.4	2.4
BRA/BTA* ratio [#]	0.85	1.0	1.0
BTA [m^2]	176.5	1120	3600
Footprint (or roof) area [m^2]	82.5	269.2	2201.3
Ratio footprint/BRA	0.55	0.24	0.61
Area Windows [% BRA]	0.15	0.15	0.15
g-value	0.5	0.5	0.5

*BRA = useful floor area (*bruksareal*); BTA = gross floor area (*bruttoareal*)

Table 6. RC values of the nine building archetypes available.

Building type	**Efficiency**	H-value [W/m^{2}K]	R_i [m^{2}K/W]	R_e [m^{2}K/W]	C_i [Wh/ m^{2}K]	C_e [Wh/ m^{2}K]
House	Regular	1.41	0.071	0.638	9.50	65
	Efficient	0.74	0.135	1.216	9.50	65
	Very eff.	0.54	0.185	1.667	9.50	65
Apartment	Regular	1.30	0.077	0.692	9.50	112
	Efficient	0.69	0.145	1.304	9.50	112
	Very eff.	0.50	0.200	1.800	9.50	112
Commercial	Regular	1.01	0.099	0.891	9.50	112
	Efficient	0.56	0.179	1.607	9.50	112
	Very eff.	0.40	0.250	2.250	9.50	112

Table 7. Long and short τ of the nine building archetypes available.

Building type	**Efficiency**	Long τ [h]	Short τ [min]
House	Regular	48	35
	Efficient	91	67
	Very eff.	124	92
Apartment	Regular	84	40
	Efficient	159	76
	Very eff.	219	105
Commercial	Regular	108	52
	Efficient	195	94
	Very eff.	274	131

Table 8. Values of the factors applied to the disturbances.

Building type	Efficiency	α_s	α_i	α_v
House	Regular	1	0.3	-
	Efficient	0.4	0.3	-
	Very eff.	0.3	0.2	-
Apartment	Regular	1	0.3	-
	Efficient	0.4	0.4	-
	Very eff.	0.3	0.3	-
Commercial	Regular	0.3	0.4	1
	Efficient	0.35	0.2	1
	Very eff.	0.35	0.1	1

Table 9. Default values for the calculation of ventilation losses.

		ΔT = 4 °C	Occupied (6h - 18h)		Unoccupied (18h - 6h, weekends and holidays)	
Building type	Efficiency	c_{air}*ΔT [Wh/m^3]	m [m^3/m^{2}h]	q_{vent} [W/m^2]	m [m^3/m^{2}h]	q_{vent} [W/m^2]
Commercial	Regular	1.32	7	-9.24	2	-2.64
	Efficient	1.32	7	-9.24	2	-2.64
	Very eff.	1.32	6	-7.92	1	-1.32

Table 10. Initial indoor temperature for the nine building archetypes, calculated using the NS3031:2014 standard climate data.

	House			Apartment			Commercial		
Month	**Reg**	**Eff**	**Vef**	**Reg**	**Eff**	**Vef**	**Reg**	**Eff**	**Vef**
January	18.67	19.66	19.78	19.59	20.55	20.71	20.26	19.98	20.27
February	18.67	19.96	19.96	19.48	20.69	20.78	20.93	20.52	20.60
March	19.46	20.54	20.97	19.90	20.82	21.43	20.83	20.65	21.02
April	21.38	22.19	23.12	21.36	21.89	23.13	20.20	19.69	19.51
May	23.06	22.36	22.98	22.63	21.51	22.51	20.74	20.41	20.78
June	24.88	24.04	23.94	24.06	22.71	23.04	24.46	24.49	25.32
July	24.31	24.21	24.17	23.59	23.05	23.41	25.54	26.17	28.81
August	24.42	22.96	22.87	23.95	22.09	22.31	23.34	23.50	24.63
September	21.73	20.08	20.71	21.72	19.78	20.63	18.58	18.51	19.55
October	20.91	20.56	21.73	21.36	20.88	22.17	17.78	17.40	17.63
November	19.45	19.96	20.55	20.19	20.65	21.30	19.14	18.86	19.07
December	19.10	19.86	20.10	20.01	20.74	21.01	19.67	19.42	19.79

Table 11. Default values of installed capacities of the heating components and the domestic hot water tank.

Building type	**Efficiency**	Base heating load dimensioning [%]	Base heating component [W/m^2 -- kW]	Top heating component [W/m^2 -- kW]	Heat emitter [W/m^2 -- kW]	DHW tank size [lt/m^2 -- lt]	DHW tank coil power [W/m^2 -- kW]
House	Regular	50%	25.0 -- 3.7	64.8 -- 9.7	60.0 -- 9.0	1.25 -- 188	12.5 -- 1.88
	Efficient	50%	13.2 -- 2.0	36.6 -- 5.5	31.7 -- 4.8		
	Very eff.	50%	9.6 -- 1.4	27.9 -- 4.2	23.0 -- 3.5		
Apartment	Regular	50%	24.0 -- 26.9	67.4 -- 75.5	57.6 -- 64.5	0.86 -- 960	10.7 -- 12.00
	Efficient	50%	12.7 -- 14.2	40.3 -- 45.1	30.4 -- 34.1		
	Very eff.	50%	9.2 -- 10.3	31.9 -- 35.8	22.1 -- 24.8		
Commercial	Regular	50%	28.6 -- 103.1	72.7 -- 261.9	68.8 -- 247.5	0.29 -- 1 029	5.1 -- 18.42
	Efficient	50%	16.1 -- 57.8	42.5 -- 153.0	38.5 -- 138.7		
	Very eff.	50%	11.4 -- 41.0	31.3 -- 112.7	27.3 -- 98.3		

Table 12. Parameters for the use of Firewood as space heating component.

	Weekday		**Weekend**	
SH Load covered %	House	Apartment	House	Apartment
0:00-6:00	0%	0%	0%	0%
7:00	12%	12%	0%	0%
8:00-15:00	0%	0%	19%	19%
16:00-23:00	19%	19%	19%	19%
Firewood overall efficiency*	35%	35%	35%	35%
Period	Stop	14.05 23:00	Start	15.09 00:00

*Assumption that includes the "control efficiency", i.e. that indoor temperature may swing above the setpoint that is usual for the other heat sources (typically around 20-22 C). This may partly be intentional as well, i.e. use of firewood of additional heating comfort. These parameters, when applied to a national stock, as in Sartori *et al.* (2023), give a good match with statistics on overall firewood consumption in Norway.

Table 13 – Parameters for the PV systems, Batteries, and Electric Vehicles.

	House	Apartment	Commercial
PV system			
Roof area for PV [%]	50%	50%	50%
PV system overall efficiency [%]	20%	20%	20%
PV capacity per m2 installation [Wp/m^2]	200	200	200
PV capacity per BRA [Wp/m^2]	55.00	24.03	61.15
PV capacity per building [kWp]	8.25	26.92	220.13
Tilt angle [°]	30	10	10
Orientation distribution			
South	50%	0%	0%
East	25%	50%	50%
West	25%	50%	50%
Battery			
Batt. capacity per PV installed [kWh/kWp]	0.50	0.50	0.50
Usable battery capacity [%]	80%	80%	80%
Batt. capacity per building [kWh]	4.12	13.46	110.07
Usable batt. capacity per building [kWh]	3.30	10.77	88.05
Initial State-Of-Charge (SOC) [%]	0%	0%	0%
Dis/Charge rate per hour, relative to cap. [%]	80%	40%	40%
Dis/Charge rate per hour [kWh/h]	3.30	5.38	44.03
Efficiency charging [%]	95%	95%	95%
Efficiency discharging [%]	95%	95%	95%
Electric Vehicles			
Annual energy use per EV unit [kWh/y]	2 342	2 342	5 483
Annual energy use per m2 [kWh/m^{2}y]	15.6	26.8	7.6
Annual energy use per building [kWh/y]	2 342	29 978	27 414
Nr. of EVs per household	0.80	0.80	-
Nr. of EVs per building	1.0	12.8	-
Nr. of charging points per building	-	-	5.0
Utilization factor	1.00	1.00	1.00
Nr. of EVs per 1000 m^2	6.67	11.42	-
Nr. of Charging points per 1000 m^2	-	-	1.39

VISION:

«Sustainable neighbourhoods with zero greenhouse gas emissions»

Research Centre on
ZERO EMISSION
NEIGHBOURHOODS
IN SMART CITIES

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