Building Energy Performance Evaluation of a Norwegian single-family house applying ISO-52016

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Abstract
In the following work, we have implemented a version of the hourly method in the ISO 52016-1:2017 standard, informed by the central input table in the SN/TS 3031:2021 specification, including a building energy supply system modelled according to the specification. A case study shows that the model compares well to measurements in unoccupied periods and that openly available gridded weather data can substitute data collected by the weather station on site. A more refined representation of boundary conditions and additional user inputs may be needed for other housing typologies than what can be recreated from the table, but we find that some of this information can be stipulated using open spatial datasets and tools. The results are presented in a web-service dashboard, maintaining continuity with operation phase data collection.

Introduction
In the Nordics, heating constitutes the predominant part of building energy consumption. When heating demand peaks in cold, dry, and calm weather in winter, customers also experience the highest electricity prices. Norwegian household energy consumption is based on electricity to a much larger degree than in neighbouring countries (Aanensen and Holstad 2018). Norway has a high share of single-family houses (50 %) tied to a significant part of the building energy use and has, like many other countries, recently upgraded all customers' utility meters to smart electricity meters. From mid-2022, a new network tariff will introduce time-of-use and capacity principles to households (OED 2021). Real-time monitoring of granular (or as reported by utilities with one day delay; hourly) consumption may facilitate new services and value streams, unlocking energy and cost savings to society (Elhub 2021). Research shows that methods to obtain the heat dynamics of buildings can be key to taking full advantage of smart meters, including demand-side flexibility and Internet-of-Things applications for smart homes (Fitton, Bouchié et al. 2021).

Building energy calculations from the design phase are rarely used in operation or followed up by analysis after construction and among the existing housing stock in Norway, the energy performance certificates have little utility beyond obtaining a label. We identify a need to perform energy calculations on realistic climate and use and question if aggregated information can be adequate.

This research aims at verifying the suitability of a scalable approach to link design and operational performance. An untapped potential may exist in utilising design documentation, open datasets and stipulated values combined with model structures that can be informed by prior information and easily compared to (or directly calibrated with) measurements. For homes, these actual forward calculations can be made part of the energy label scheme by exchanging information between models, open datasets, and billed energy history. As the current interface for energy labelling has no export functionality, the paper investigates to what extent the reporting table for central data in the calculation standard (see Table 1) can be used to recreate a lumped thermal network model retaining the SN-NSPEK 3031:2021 calculation requirements. The reporting table is consistent with the well-established building envelope heat loss budget and the combined building heat loss coefficient in W/(m^2 K).

Background
The challenge of improving buildings' energy performance has led to the development of many methods for building energy performance assessment in the last decades. Dynamical approaches to whole-building assessment can rely on a growing variety of spatial information, efficient algorithms, and cloud computing, meaning that the level of detail is not merely limited to available computational capabilities or locally stored data. Whereas detailed physical methods require complete descriptions, data-driven alternatives to physical modelling, represented by black-box and grey-box modelling, require detailed monitoring data (Fitton, Bouchié et al. 2021). Varying monitoring data availability or insight into what governs energy use are adherent limitations of purely data-driven approaches. On the other hand, physical models simulate the expected design, not actual performance, unless calibration is performed, which is typically expert work and requires information that can be hard to obtain.

Several simplified dynamical models and tools have been developed to obtain a compromise between detail and accuracy by balancing data retrievability. Some of these model structures have also been modified and demonstrated with so-called grey properties that combines physical descriptions and operation data to identify performance coefficients (Chong, Gu et al. 2021), but larger model structures with a large number of unknowns risk that the parameters become unidentifiable (Yu, Georges et al. 2019). However, Bayesian calibration procedures show great potential in exploring large parameter spaces allowing experimentation with higher model complexity (Lundström and Akander 2020). EN ISO 13790:2008 was the first international standard describing a dynamical hourly method comprising a resistor-capacitor (RC) network analogy with five resistors and one capacitor (5R1C). It was withdrawn in 2017 and replaced with the EN ISO 52000 family of global (EN) standards and revised European (CEN) standards. The complete set of Energy Performance of Buildings (EPB) standards, including EN ISO 52016-1:2017, the successor of EN ISO 13790:2008, offers a set of harmonised methods to assess the energy performance of buildings. At the same time, the EPB standards are open to including alternative validated methods so that countries can tailor them to specific national or regional features (van Dijk 2019).

As a member of the European standardisation organisation CEN, Norway adopted the new EPB standards in February 2018 but has continued using the old national standard NS 3031:2014 (first released in 2007) for building code compliance and energy certification. The technical working committee has yet to produce a national addendum or revision compatible with the EPB standards but has released a supplementary specification. SN-NSPEK 3031:2021 contains updated normative data (e.g. schedules) and formulates a simplified dynamic method to calculate the energy supply of buildings. The document focuses on energy delivery in local climate and strategies for climate correction to a reference climate, two elements that are expected to be considered for the next revision of building code energy requirements (DiBK 2021). The Norwegian energy labelling scheme is also undergoing revision. As preliminary reports have identified, better utilisation of information obtained from energy labelling may lead to greater interest in efficiency measures and conversion to local renewable energy production (Enova 2019).

Open models and data are expected to play a crucial role in developing new methods for tracking energy performance at multiple levels (Manfren, Nastasi et al. 2020). Previous works show that rearranging gridded weather data, such as the operational MET Nordic Analysis and Forecast, or global and regional reanalysis, along the time dimension make it possible to compile hourly multi-year weather datasets in seconds. Open spatial datasets can also be utilised to adjust for local sheltering and shadow conditions in a simplified manner or model surrounding buildings and vegetation in 3D in a pre-processing step (Skeie and Gustavsen 2021). Realistic evaluations spanning several years in actual local climate using computationally efficient models based on international standards, provides a basis for as-built performance evaluation, and enables comparison with measurements. Additional uses of calibrated models are providing real-time feedback, estimating energy savings, or forecasting costs based on actual price signals.

Method

The calculation framework is presented below. The paper first discusses implementing the ISO 52016-1 model using the existing ISO14N modelling framework (Lundström 2019, Lundström, Akander et al. 2019). The model validation criteria and data acquisition platform are introduced (Figure 1). Then, the input table from NS 3031 is presented using values from the case study. We list open datasets that can be utilised to represent climatic boundary conditions, including a way to weigh solar irradiance by building facades. Extra user input is discussed, and the schedules and setpoints applied to the model before it is validated on measurements.

The 52016-1:2017 method and the ISO14N model

The thermal network of ISO14N is a lumped and simplified implementation based on the ISO 52016-1:2017 standard (Lundström 2019, Lundström, Akander et al. 2019). Building elements are lumped into four series of resistances representing either roofs, floors, walls, or windows. This simplification is still closer to physics than ISO13790:2008, which lumps all building envelope transmission losses into two resistances in series. Other notable differences:

- Infiltration loss is modelled with the AIM-2 model, which provides wind and stack driven flow. ISO 16798-7, referenced in 52016-1 and SN-NSPEK 3031:2021, are open to validated empirical models.
- Surface convection resistances are wind dependent and pre-calculated in a matrix, enabling the use of empirical algorithms for surface heat exchange.

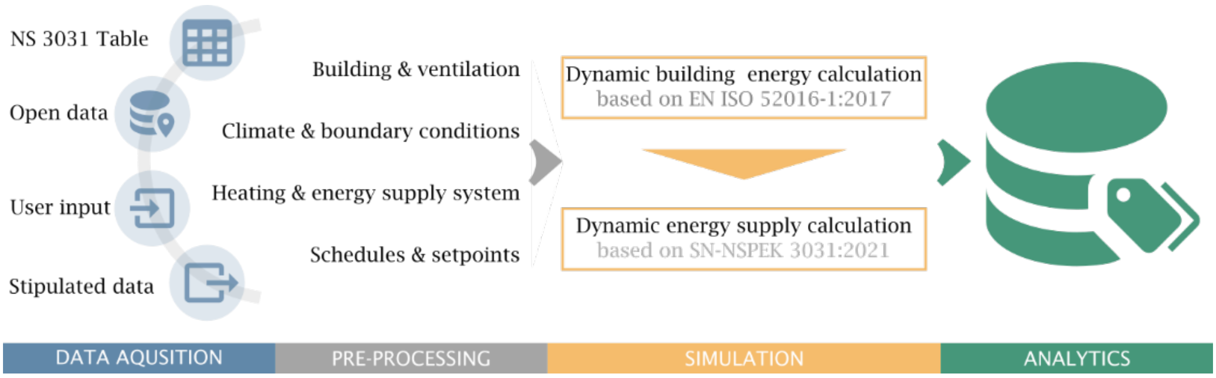

Figure 1: Modular calculation framework

- The framework is available in multiple configurations, a version where building elements are represented by three nodes instead of the five nodes described in the standard and an adapted state-space form (2020).

In the following work, we have generalised the model with five nodes per building element from (Lundström 2019, Lundström, Akander et al. 2019), ISO22N, to represent single-family housing typologies and made the following changes according to SN-NSPEK 3031:

- Implement ideal heating and cooling through an iterative procedure instead of a P-band controller.
- Heating or cooling is emitted to air and surfaces (by a ratio) based on an indoor air temperature setpoint adjusted for an equivalent air temperature of non-ideal regulation.
- Include extra heat loss from built-in heating elements.
- Ventilation loss includes heat addition from fans and recovery wheels that adjust to the supply setpoint.
- Floor elements on the ground are modelled according to EN ISO 13370:2017. Floor elements towards ventilated crawl spaces are modelled like external walls (except omitting longwave radiation to the sky).

The simple model structure is flexible and could be expanded to express walls, roofs or floor slabs with more than one external boundary condition, e.g. sloping roofs with different solar exposure or multiple floor elements, approximating a component-based approach. Noting that the thermostat control differs between ours and other implementations, a comparison between ISO14N, the EN ISO 52016-1:2017 supporting calculation sheets (van Dijk 2019), and EnergyPlus software for reference BESTest cases exists (Grassi, Piana et al. 2021).

The SN-NSPEK 3031:2021 energy supply model

The implemented heat storage model is a basic accumulation model at two temperature levels, a top tank and a bottom tank. Production is prioritised to match space heating and hot water demand in each time step. The primary unit is a base heating unit, aiming first to cover the space heating demand. To simplify calculations, we assume that the top heater (electric) always meets the remaining heating demand.

The energy delivered by photovoltaic modules in kWh/h is calculated with the simple equation found in EN 15316-4-3:2017: $E_{el;pv;out} = E_{sol;pv;h} \cdot P_{pk} \cdot f_{perf} / I_{ref}$, where $E_{sol;pv;h}$ is the solar irradiation on the system in kWh/m^2, $P_{pk}$is the system peak power in kW at reference conditions (I_{ref} = 1 kW/m^2). SN-NSPEK 3031 gives recommendations on how to estimate the system performance factor f_{perf}; including temperature-dependent losses for semi-integrated panels.

Validation

The case building is the ZEB Living Lab, Trondheim. The building is a single-family house with several space-heating and energy-generation systems, representing a challenge to model due to the many possible operation modes. In 2021, the building was largely unoccupied, which offers an opportunity to validate the model. The underfloor heating was used in all of 2021, which enables a comparison of measured space heating use and calculated heating need using the actual room temperature setpoint, information about the ventilation unit operation and appliance electricity uses as input. The whole-facility electricity use, including generation and storage losses, was evaluated for October 2021, a month when the heat pump and solar collector were out of service; thus, the building was heated by direct electricity in the accumulation tank. The building utility meter and metered PV production was used in this validation.

The actual model is validated on mean bias error (MBE) normalised to make the values comparable, and the coefficient of variance (CV) of the root mean square error (RMSE), calculated on hourly, daily and monthly averages. In evaluating how well the sourced gridded weather data represent outdoor temperature, wind speed, and global horizontal irradiance measured on-site, the mean absolute error (MAE) was also included in the analysis. Like MBE, MAE is the average difference between the observations and model output. Still, in MAE scores, the sign of these differences is ignored, so cancellations between positive and negative values do not occur. The CV(RMSE) is neither subject to cancellation errors, so it is recommended to verify the accuracy of as-built models on CV(RMSE) (Ruiz and Bandera 2017).

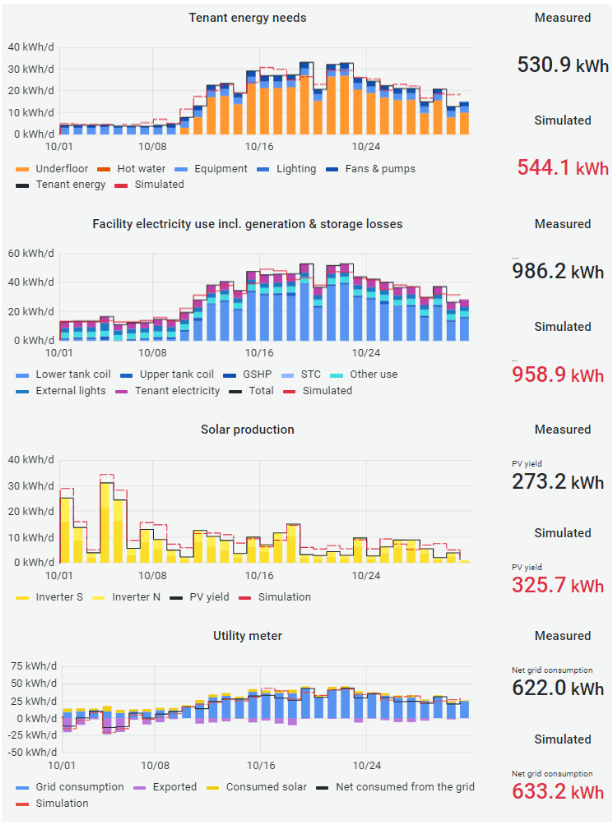

Figure 2: shows the modelled (red line) and measured (black line) tenant energy needs, facility electricity use, net electricity consumption, and solar production per day in October 2021, including net grid consumption and self-consumption metrics.

Analytics

The model output is combined with the monitoring data in a time-series database and visualised using the observability platform Grafana (Figure 2). Four diagrams represent the detailed energy use, aggregated hourly, daily and monthly. Tenant energy needs is the term chosen in this work for calculation point A in SN-NSPEK 3031:2021 (Netto energibehov, in Norwegian), which consists of thermal energy needed for space heating and domestic hot water heating, and electricity use for appliances, lighting, ventilation fans and distribution pumps. Auxiliary electricity needed for outdoor lighting and operating the detailed monitoring and automation system in the technical room is accounted for under facility electricity use, including distribution and storage losses (calculation point B) and electricity used for heat generation, totalling the whole facility electricity usage. The monitored electricity generation from the two inverters and the grid consumption and export measured by the building utility meter is visualised in the two bottom panels and used to calculate self-consumption and net consumed electricity from the grid. These two diagrams and consumption metrics are also available in a popular home automation platform currently being implemented in the building (Schoutsen 2021). In Norway, energy metrics in the automation platform can be updated once per day from the data reported by utilities or in real-time by interfacing the smart meters' Home Area Network (HAN) port.

Data acquisition and pre-processing

Building data & ventilation

Geometry input is needed in building energy modelling. An advantage of most simplified hourly model workflows using an RC-network analogy is that zones do not need to store 3D geometry or adhere to geometric and topological requirements, like closed volumes. Instead, inputs are specified per construction elements: Net surface area and orientation of roofs, floor slabs, facades and window components are used to calculate heat transfer. This component-based and non-geometrical approach provides the practitioner with great flexibility. It ensures a heat loss budget following the procedure laid out in the calculation standard used for building code evaluations.

The leading tool for compliance with the national energy requirements in the Norwegian building code has an XML-file format that can exchange model information at the component level. However, the Norwegian calculation standard has not provided a common format; only a normative input data table is specified. It must be used in reports to trace and verify inputs and assumptions. Consequently, compliance tools generate the table automatically as an output.

However, the component level is not reflected in the data table (Table 1), which only provides aggregated surface areas and U-values for walls, roofs, floors and apertures. The Appendix recommends specifying the fraction of building envelope parts exposed to non-heated zones, air, and ground. The effective U-value for unheated zones and the equivalent U-value for floors and basement walls towards the ground are to be given in the table. If these vary, solar factors g_t shall be specified by façade orientation and as an average from (May-August). The table also reports the internal loads used in calculations (not shown in Table 1). Overshadowing from building form and site obstructions is not registered in the tables.

Summing the values in Table 1, the thermal transmittance losses of the building are 0.72 W/m^{2}K (envelope transmission), whilst the infiltration losses and ventilation losses are 0.08 W/m^{2}K and 0.07 W/m^{2}K, respectively when calculated according to the standard.

Whilst the airtightness design value (n50) of 0.50 h^{-1} (Goia, Finocchiaro et al. 2015) was verified with blower door tests during construction, the estimate was adjusted to 1.00 h^{-1} based on recent thermography, which revealed air leaks around the sliding door gaskets and main entrance door (Skeie 2020). The calculated heat loss of 87 W/K corresponds well with results from co-heating tests in 2017, indicating that the total envelope heat loss (including ventilation loss) is in the range 77 – 100 W/K and the internal heat capacity to 3 – 5.5 kWh/K (Vogler-Finck 2017). A second study reached similar ranges (Yu, Skeie et al. 2022). Model validation in IDA-ICE using data from the same co-heating tests estimated the value to 83 W/K (Clauss, Vogler-Finck et al. 2018).

Table 1: Input data to the building model.

Description		**Value**
Areas [m^2]	External walls (A_{ew})	*142*
	Roof (A_{rf})	*112*
	Floor (A_{gf})	*101*
	Windows, doors, glazed units (A_{gl})	*42*
Heated floor area (A_{fl}) [m^2]		*101*
Heated air volume (V) [m^2]		*342*
U-value for building envelope components [W/(m^{2}K)]	External walls (U_{ew})	*0.12*
	Roof (U_{rf})	*0.11*
	Floor (U_{fl})	*0.10*
	Windows, doors, glazed units (U_{gl})	*0.73*
Normalized thermal bridge value (Ψ'') [W/(m^{2}K)]		*0.03*
Normalised heat capacity (C'') [Wh/(m^{2}K)]		*51.00*
Airtightness value (n_{50}) [h^{-1}]		*1.00*
Total solar factor (g_t) for window and shading		*0.30*
Average frame factor (FF)		*0.40*
Estimated average temperature efficiency for ventilation heat recovery unit in the heating season (η''_T) [%]		*85.0*
Average specific fan power (SFP) in the specified operating time of the ventilation system [kW/(m^3/s)]		*1.10*
Average specific pump power (SPP) for space heating system [kW/(l/s)]		*0.50*

Building shape and context data inform shading and insolation calculations. In software following the methodology of the EPB standards, these are text-based inputs specified on the component level. Many tools have been developed to support geometry creation for building energy models. Previous publications show how geographic information systems (GIS) can inform building energy modelling (Skeie and Gustavsen 2021).

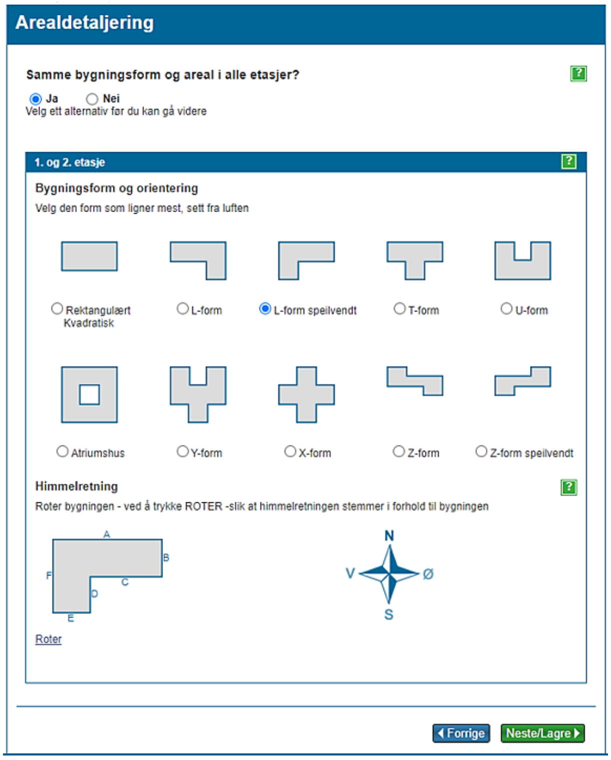

Figure 3 building orientation and geometry input to the graphical user interface of energimerke.no.

In the web interface of the Norwegian energy labelling scheme, a 2D floor plan is used to define the surface areas of building components (Figure 3). Overlaying these shapes on actual maps would make building modelling easier and enable extracting information about the surroundings from open spatial datasets, as described in the next section. Outlines can also be utilised to approximate building self-shading, although an accurate representation of overhangs requires 3D geometry or detailed manual inputs.

Climate, site & boundary conditions

Climate data were obtained from the following open datasets (Table 2). Site information was sourced from the national elevation model, and the building footprints were sourced from the Inspire Buildings core 2D layer, both by the Norwegian Mapping and Cadastre Authority.

Table 2. Climate and site data.

Description	Input
MET Nordic Analysis and Forecast	T_{2m} U_{10m} I_{GHI} C_{sky}
ECMWF Reanalysis v5 (ERA5)	T_{2m} U_{10m} I_{BNI} I_{DHI}
CAMS radiation service (CAMS)	I_{BNI} I_{DHI}
seNorge observational gridded dataset	S_{wde}; (snow depth)
Høydedata national elevation model	H_b λ_p λ_w F_{sh}

Shading masks for each façade were approximated using a simplified building footprint and the national elevation model in 1-meter resolution. The approach to obtain building height H_b, shading masks F_{sh}, and morphology parameters plan area density λ_p and wind sheltering factor λ_w are described in (Skeie and Gustavsen 2021). The shading mask and solar irradiance is calculated using the R-package solarCalcISO52010 (Lundström 2018).

Heating and energy supply system

The building has three underfloor heating circuits monitored by two Kamstrup Multical 602 thermal energy meters. The underfloor heating pipes are in a well-insulated floor construction below a layer of hardwood flooring. The thermal efficiency is 98 %; thus, extra heat loss from built-in heating elements is negligible. However, the piping from the tank to the manifolds in the technical room was uninsulated at the time of the measurements, leading to a substantial storage and distribution loss (~30%), effectively heating the technical room. In this analysis, the technical room is not considered part of the thermal zone, and the internal wall towards the technical room is treated as adiabatic. The storage and distribution losses are not part of the heat balance but are included in the whole-facility energy use, including 343 Watt (3.4 W/m^2) for operating the building automation and data acquisition system, outdoor lighting, and domestic hot water electric coil (incl. tank losses).

Schedules & setpoints

Heating and ventilation setpoints are usually constant or vary daily with night setbacks and can be collected from the home-automation system. The following analysis uses the space heating and ventilation setpoints and the fan mode as inputs to the model. The internal heat gains are considered constant in the assessment period. In January, the heating setpoint adjusted for non-ideal regulation was 19.7 degrees and adjusted down to 17.3 degrees onwards. Internal gains from appliances are continuous 110 Watt (1.1 W/m2).

Evaluation of actual performance

First, the previous year of observations from the weather station on the roof was compared to the gridded weather data proposed in the study. Table 3 shows that the MET Nordic regional analysis, with its hourly update cycle, captures the local air temperature better than the ERA5 global reanalysis (available with a five-day delay). This finding is expected due to the higher spatial resolution of the regional model and 1 km spatial interpolation assimilating many observations collected in near real-time. The table also includes a second air temperature sensor on the north façade (wall sensor, table 3). Although both sensors are shielded from direct solar irradiance, deviations occur in the daytime, resulting in MAE and RMSE scores nearly on par with the analysis. The gridded products achieve relatively low errors but could benefit from bias correction using a period of measurements from the weather station, nearby stations, or other products.

Table 3. Error metrics for the hourly observed outdoor temperature at the rooftop in 2021. Negative values are model underestimations (MBE = PM;year − OM;year).

Product	Mean	MBE	MAE	RMSE
$O_{M;year}$, roof	5.6 °C	–	–	–
MET, 2m	6.2 °C	0.6 °C	0.8 °C	1.0 °C
ERA5, 2m	5.2 °C	- 0.4 °C	1.1 °C	1.5 °C
$O_{M;year}$, wall	5.6 °C	0.0 °C	0.5 °C	0.8 °C

The analysis and reanalysis 10-meter wind speed overestimate the mean wind speed on the roof level by up to 100% (Table 4). Assuming that the analysis represents the wind in open terrain, a logarithmic site conversion and height adjustment to roof height bring the positive bias error down to 0.6 m/s. Wind speed at roof height (METc, roof) is an input to the infiltration model, and the exact relationship is also used to calculate the wind speed at mid-façade height for the surface convection algorithm.

Table 4. Annual error metrics for hourly observed wind speed at the rooftop in 2021, calculated from 10 min mean preceding observation (OM;year = 1.5 m/s).

Product	Mean	MBE	MAE	RMSE
$O_{M;year}$, roof	1.5 m/s	–	–	–
MET, 10m	3.0 m/s	1.5 m/s	1.6 m/s	2.2 m/s
ERA5, 10m	2.5 m/s	1.0 m/s	1.3 m/s	1.6 m/s
METc, roof	2.1 m/s	0.6 m/s	0.9 m/s	1.3 m/s

For solar irradiance calculations, the CAMS radiation service from Copernicus is used, which mainly relies on imaging from geostationary satellites and is available with a 1-day delay. Also available with a one-day delay is SMHI's STRÅNG analysis product, which is included for comparison only. The solar irradiance components used in the model are the direct and diffuse irradiance from CAMS-Rad, adjusted with values derived from the MET analysis when the snow model reports snow on the ground (CAMS corr., table 5). This correction improves the estimate in March and April, periods of intermittent snow cover where the current version of the satellite product consistently underestimates irradiance [-].

Table 5. Annual error for mean global horizontal radiation measured in 2021, of 2925 hours with a solar height angle >10° above the horizon (267 kWh/m² yr).

Product	Mean	NMBE	NMAE	CV(RMSE)
$O_{M;yr;zen<10°}$	267	–	–	–
MET	294	10 %	32 %	61 %
ERA5	268	0 %	27 %	39 %
STRÅNG	272	2 %	28 %	41 %
CAMS	253	- 5 %	20 %	29 %
CAMS corr.	257	- 4 %	19 %	28 %

Annual space heating need

We can see that the model can replicate the daily and monthly heating needs well compared to one year of actual measurements (black line, Figure 4). The annual heating need is underestimated by 3% (NMBE, Table 6) when the outdoor temperature measured on-site is used as input (green line, Figure 4). This bias, largest in winter, may indicate that the actual building heat loss is higher than modelled. It increases to double, ca. 7 % when relying on the outdoor temperature from the gridded analysis product as input (red line). The daily heating need is still closely replicated due to a more accurate representation of local outdoor temperature during winter's coldest hours than ERA5. Still, due to the model bias, ERA5 appears with a comparable CV(RMSE) and the lowest NMBE.

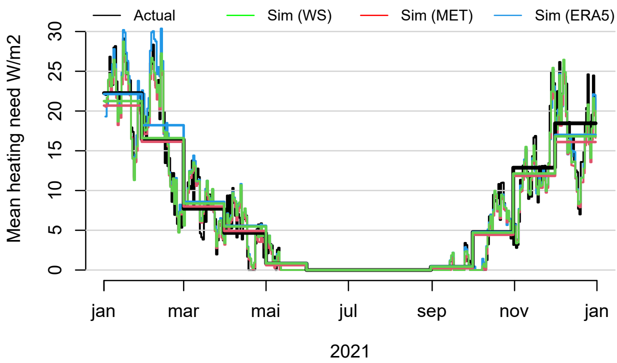

Figure 4, daily and monthly average space heating need in Watt per m2, measured (black) and simulated with outdoor temperature from weather station (green), MET-Analysis (red), and ERA5 (blue) products. See table 6 for annual error metrics.

ASHRAE Guideline 14 suggest that a model is calibrated if the NMBE is within ± 5\% and CV(RMSE) < 15\% for monthly data. The limits are twice as large for hourly data, NMBE ± 10\% and CV(RMSE) < 30 \% (ASHRAE 2014). Hourly, daily and monthly results are presented below (Table 6).

Table 6. Results of one-year space heating need calculation. The annual measured space heating need is 63.8 kWh/m2 yr. See Figure 4 for monthly values.

Timescale		NMBE	CV(RMSE)
Weather station, 62.5 kWh/m² yr	Hourly	- 2 %	101 %
	Daily	- 2 %	17 %
	Monthly	- 2 %	10 %
MET Nordic, 59.8 kWh/m² yr	Hourly	- 6 %	102 %
	Daily	- 6 %	19 %
	Monthly	- 7 %	13 %
ERA5, 64.1 kWh/m² yr	Hourly	1 %	102 %
	Daily	1 %	20 %
	Monthly	2 %	11 %

The model can be considered calibrated on a monthly or daily basis, but on hourly timestep, the criteria fail. This result is expected as the thermostat cycle and the multiple

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underfloor heating zones are not implemented and therefore not replicated well. The ideal heating routine is simply keeping the indoor air above the set point. The inclusion of local shadowing effects positively impacted the model; nevertheless, solar heat gains modelling, including assumed indoor blind position and glazing properties, is a source of uncertainty (not shown).

Annual electricity generation

The roof is fitted with REC Solar modules of 12.5 kWp, or a surface area of 79.2 m^2 and nominal efficiency of 15.8 %, a rated temperature coefficient of 0.40 and inverter efficiency of 96 %, according to manufacturing data. These values were used as input in the PV calculations (Figure 7). The two inverters are undersized, so the maximum power was limited to 4350 Watt/inverter. The final model estimate is obtained by (1) adjusting the satellite product for periods from February to April of intermittent snow cover, (2) considering shadowing effects of the roof geometry and surroundings and (3) setting PV production to zero when snowfall occurred within the last week. The hourly model closely reassembles the measured electricity generation over the year with an NMBE of 2.1 % and every month (Figure 5) indicated by the CV(RMSE) of 6.5%.

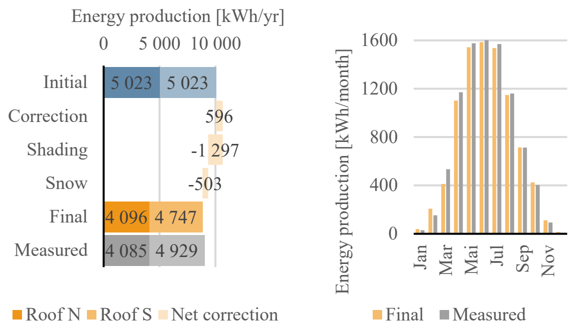

Figure 5 shows the total and monthly PV model for the initial model without accounting for site shading or snow effects, and the final model (orange) matches the measured values (grey).

One month of actual energy use

The whole-facility electricity use was evaluated for October 2021, an unoccupied month when the building was heated by direct electricity in the accumulation tank. Figure 2, in the method section, shows the model and the measurements per day, including aggregated totals and how they are presented in the dashboard. Figure 6 below visualises the hourly profiles. A black line illustrates the measurements subdivided into stacked coloured bars. From the top, the red line shows the simulated tenant need for energy (tenant electricity need and heating energy need), facility total electricity use, solar production and net grid consumption in kWh/h (utility meter).

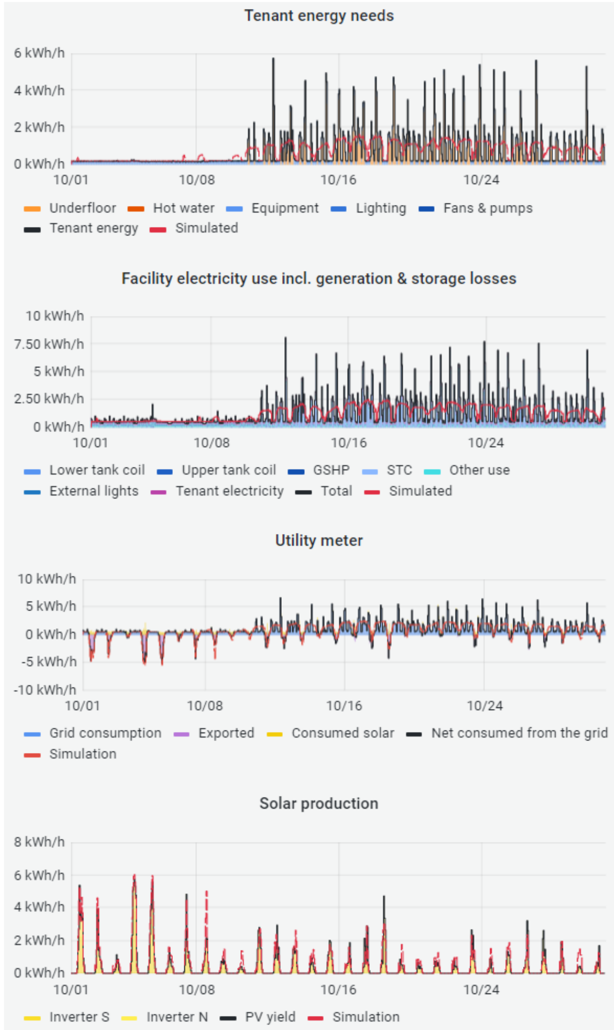

Figure 6 shows a screenshot from the observability platform presenting the model (red line) and detailed measurements of tenant energy needs, facility electricity use, net electricity consumption, and solar production per hour in October 2021.

The building utility meter and metered PV production was used in this validation, and the facility electricity use equals the sum of self-consumed electricity use and grid consumption. The two PV inverters are single-phase, meaning that one phase of the 3-phase electric coil is used to heat the accumulation tank and the circuits connected to the remaining phase draw from the grid at all times, reducing the potential building self-consumption. This aspect was not modelled, but the calculation step of 1 hour and poor match between hourly calculated heating need and measured heating use have a greater impact on the results (Table 6). Still, the daily CV(RMSE) is comparable to what was obtained annually for space heating (Table 5).

Table 6. Results of October 2021, an unoccupied month when the building was heated by electricity (in the tank).

Timescale		**Mean**	**NMBE**	**CV(RMSE)**
Net grid el.	Hourly	0.8 kWh/h	2 %	127 %
	Daily	20 kWh/d	2 %	25 %

PV gen. el.	Hourly	0.4 kWh/h	19 %	91 %
	Daily	8.8 kWh/d	20 %	32 %
Facility el.	Hourly	1.3 kWh/h	- 3 %	93 %
	Daily	32 kWh/d	- 3 %	13 %
Tenant need	Hourly	0.7 kWh/h	2 %	125 %
incl. thermal	Daily	17 kWh/d	3 %	19 %

For these calculations, no data from the weather station was used. The outdoor temperature, sky conditions, wind speed, and solar irradiance were sourced from the analysis and satellite radiation service, limiting the need for measurements. Since the analysis is the best estimate of the conditions formed by combining the operational weather forecast with observations, using the forecast model on which the analysis is based would be straightforward to implement.

Discussion

The validation shows that the simplified model composed of the NS 3031 table and minimal input can replicate the building's space heating need and that even the net consumption from the grid (purchased electricity) is well represented in unoccupied periods. The case is a well-insulated house with underfloor heating where operating conditions are known (internal gains, heating setpoint and ventilation unit settings are additional inputs). According to the quality thresholds in the ASHRAE guideline 14 (ASHRAE 2014), the model is validated when comparing the daily and monthly actual measured and simulated heating needs for an entire year. The discrepancies occurring on an hourly level due to the idealised heating control were not investigated further. Instead, future works should investigate the temporal dynamics, e.g. by running in free-floating mode (with temperature as output) and expand to methods that deal with model calibration, parameter estimation and input uncertainty.

For other cases or housing typologies, a more refined representation of U-values and surface areas or additional information about building boundary conditions may be needed to accurately represent constructions below ground or building self-shading and over-shadowing effects from the surroundings. We find that some of this information can be stipulated using open spatial datasets and propose that existing and new EPB tools should be developed to take advantage of this information. For example, 2D plan building geometry overlaid on maps can provide a starting point for more detailed component-based assessments or help recreate the geometry of the building and surroundings in 3D.

The second part of the study aimed to evaluate open spatial web services that can provide weather data for actual local conditions. Whereas outdoor temperature is relatively easy to measure, the monthly heating need in winter was slightly closer to measurements when relying on the weather station at the site. The advantage of a gridded product like MET Analysis and Forecast is obvious if actual assessments are carried out at scale or if the models are to be tailored for forecasting purposes.

Conclusion

This study demonstrate that models created from the methodology in the Norwegian calculation standard for building energy performance calculation can have an extended service life in an operational setting. A model of the ZEB Living Lab building in Trondheim was created in a version of the ISO14N framework based on the EN ISO 52000 family of EPB standards. Further investigations are planned on how to give feedback on in-situ performance to occupants and how to model the buildings energy balance with other heating technologies, including the grid interaction on different temporal scales and forecasting horizons. Demonstration projects like the ZEB Living Lab, can play a valuable role in adopting solutions for the realisation of energy flexible and efficient buildings that can utilise local energy resources.

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