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An approach towards sustainable renovation—a tool for decision support in early project stages

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Abstract

Reducing greenhouse gas (GHG) emissions through energy reduction in buildings is a high priority for policy-makers in the European Union and elsewhere. However, although long-term sustainability targets exist on the societal level, it is not obvious how these targets may trickle down to individual sectors and further down to specific organizations or buildings. The aim of this paper is to illustrate an approach for evaluating renovation measures in order to identify appropriate target levels in early project stages and what is needed to achieve a number of proposed sustainability targets. The evaluation approach is supported by a tool that can be seen as an aid to making rough estimations of the environmental impacts. Sustainability target levels in a Swedish context are presented for three issues: operational energy use, GHG emissions due to total energy use for building operation, and embodied GHG emissions due to production of materials. The approach to support well-grounded retrofit decisions is shown with a case study. The tool developed, in combination with a suggested step-by-step evaluation approach, provides an effective way to evaluate various potential improvements, and their consequences, in early project stages. However, other tools with similar functionality may be used. Results from the case illustration imply that it is possible to achieve the proposed sustainability targets for operational energy use by

implementing nine measures. However, the targets for GHG emissions for operational energy use and embodied GHG emissions were not achieved because of an energy supply with too high a share of non-renewable fuels.

Key words: Building renovation processes; Evaluation procedure; Sustainability targets; Greenhouse gas emissions; Energy-efficiency; Embodied emissions.

1 Introduction

Reducing greenhouse gas (GHG) emissions through operational energy reduction in existing buildings is a high priority for policy-makers in the European Union and elsewhere. Although long-term climate targets exist on the societal level, it is not obvious how these targets may trickle down to individual sectors and further down to specific organizations, buildings, or even projects. That is, what levels regarding, e.g., operational energy use or GHG emissions need to be targeted in individual projects to be in line with long-term targets at societal or sector levels?

Far-reaching renovations that achieve high reductions in energy demand and GHG emissions exist (see e.g. www.annex56.org) but are still rare [1]. Barriers to implementation of renovation processes for more sustainable buildings have been investigated by, e.g., Häkkinen and Belloni [2], Thuvander *et al.* [3], Cattano *et al.* [4], and Olsson *et al.* [5]. In addition to the fear of high investment costs and problems with profitability, key barriers identified in these studies include a lack of knowledge about sustainability issues, insufficient knowledge of building stocks, a lack of simplified evaluation tools (for decision making), and a lack of coordination between energy-saving and other measures. Finding ways to overcome similar barriers is crucial and requires identification and development of sustainability management procedures.

Moreover, the current unilateral focus on impact in the use stages is beginning to be questioned. More and more studies point to the fact that apart from the use stage, the product stage of building life cycle impact is becoming increasingly significant [6-12]. Thus, with an increasing significance of impacts associated with material production, the need for a life cycle perspective in renovation processes also becomes more apparent. A review of ongoing

and recently ended projects in Europe found 36 projects and 11 tools dealing with various “sustainability aspects” concerning renovation of buildings [13]. Seven of the reviewed tools included Life Cycle Cost (LCC) calculations and six tools included some kind of life cycle approach or environmental assessment. Furthermore, the environmental assessments vary from simplified Life Cycle Assessments (LCAs) dealing with a few impact categories to just considering CO₂ emissions due to energy demand for building operation. There are a very limited number of identified tools that include a combination of an LCC and LCA approach.

Decisions about building design such as orientation, shape, structure, degree of insulation, size of windows, and type of HVAC systems are made early on in the building process, typically in the concept design stage, where knowledge of the future building is still limited. These decisions will then govern and restrict further detailed designs of the building, and thus its environmental performance over its life cycle [14-16]. This building process is similar both in new construction and in renovation of existing buildings; however, in renovation projects, many preconditions and boundaries are already fixed. According to Shi and Yang [17], there is an understanding that decisions made in the conceptual design stage have the largest impact on the overall environmental performance of the building.

The aim of this paper is to present an approach that enables improved decision-making in the renovation process with respect to supporting the achievement of long-term sustainability targets of the building stock. This is done through:

- The demonstration of a working procedure to discuss and formulate relevant but challenging environmental targets in early stages of a renovation project, as well as outlining a way to identify which measures could be focused on for reaching such targets. As part of the procedure an evaluation tool called BECEREN (Basic Energy, CO₂ and Cost Estimation in Renovation) is used. The tool can be seen as an aid to making rough estimations of the environmental impacts over the dominant life cycle stages of a building, addressing aspects such as contribution to climate change, energy demand, and cost;
- The introduction of long-term environmental targets regarding three important aspects: energy use for building operation, GHG emissions due to total energy use for building operation, and embodied GHG emissions due to the production of materials;
- The illustration of the above mentioned approach, combining the use of the tool and the long-term environmental targets, on a case study building.

The outline of the paper is as follows. In *Section 2*, the tool development process is described together with a general description of the BECEREN tool. Proposals of quantified target levels for some selected environmental aspects are presented in *Section 3*. The use of the tool in combination with the environmental targets is illustrated with a case study; the case study building is presented in *Section 4*. The tool was used to evaluate potential building improvements in the case study building; the evaluation procedure and the case study illustration are presented in *Section 5*. *Section 6* discusses the results. It should here be noted that other tools or a combination of other tools, with the same purpose as the BECEREN tool could be used.

2 The BECEREN tool

2.1 The tool development process

The decision support tool originated in 2008 and has gradually been developed through a number of projects [7, 14, 18-19]. In the development process of the latest version of the tool, which is called BECEREN, a number of companies, including six Swedish property owners, were involved in a reference group. These companies represent both private and public actors, as well as both small and large organizations. A first version of the BECEREN tool was tested and discussed in a workshop with reference group companies and other stakeholders who were selected based on targeted end users of the tool. Participants attending the workshop were private and public property owners, consulting companies, governmental organizations, and external researchers. In total, 14 people representing 11 different organizations attended the workshop. Proposals that emerged during the workshop were embedded in later versions of the tool in order to consolidate its use among practitioners. In the existing version of the BECEREN tool, the energy calculation module was improved and an LCC module was added. In order to present the results from the economic evaluation in the most practitioner-oriented way, the LCC module was developed in an iterative way with the reference group and through separate discussions with targeted end-users.

2.2 General description of the BECEREN tool

The BECEREN tool's purpose is twofold. Firstly, it is designed to easily evaluate different improvement options for a specific building regarding energy use, contribution to climate change, and life cycle cost. Secondly, it is designed to elaborate relevant environmental targets for operational energy use and contributions to climate change in renovation projects

while also determining an indicative figure of LCC for different measures. The BECEREN tool includes predefined improvement measures in contrast to similar tools where the user needs to input material requirements and costs for each improvement before the evaluation can start [20-21]. The different improvements in the BECEREN tool are classified in three categories: *improvement options*, which refer to any improvement; *improvement measures*, which relate to physical measures that cannot be seen as renovation measures (e.g., installing PV-cells); and *renovation measures*, which relate to physical improvements such as change of windows. The principal design of the BECEREN tool is shown in *Figure 1*.

Figure 1: Principal design of the BECEREN tool. The imperative basic building data together with given values in the tool are used to present default values for optional building data.

The user only needs to insert a limited amount of basic building data (see *Figure 1*) in order to start the evaluation of a building. From entering the basic building data, the tool uses given values to present default values for optional building data parameters. Default values are based on typical designs from various eras. However, if available, the user can insert more accurate input for any of the parameters under Optional building data (see *Figure 1*).

A number of default improvement options consisting of building envelope measures, additional improvement and optimization options, and different energy sources are included

in the tool. All improvement options are described and, where suitable, priced, amounts of materials used are listed, and embodied GHG emissions are available for the included materials. The output sheet in the tool is where different improvement options and cost parameters are tested. Any combination of improvement options can be tested and the user immediately gets the results in tables and graphs. The current number of improvement options available to choose from in the BECEREN tool is shown in *Table 1*. This list of improvements is not a complete list of potential improvement options but rather a number of options that are typical but also different enough to allow for diversity. The list of options may be enlarged successively.

Table 1: The number of alternative improvement options and predefined changes to choose from, currently available in the BECEREN tool.

available in the BECEREN tool.

Energy and climate			Number of improvement options		Number of cost change options	
Heating demand	Transmission losses		Exterior walls	4*	Annual energy price increase rate (in percent)	12
			Walls towards ground	1*		
			Foundation	1*	Discount rate (in percent)	12
			Attic	3*		
			Windows	3*		
			Entrance & balcony doors	4*		
			Thermal bridges	-		
	Ventilation losses		Ventilation system	3*		
Hot water		Production and recovery	3**			
Efficiency improvements	Equipment		Lighting and white goods (domestic electricity)	3**		
			Building automatization	-		
	Local energy source	Heat	External heat pump	1**		
			Solar collectors	1*		
		Electricity	PV cells	1*		
			Wind turbine	1**		
			Energy source	External heat source		Heat source 1
Heat source 2	24**					
External electricity source	Operational elect.	Electricity source		7**		
	Domestic elect.	Electricity source		7**		

*Embodied GHG emissions have been calculated specifically for the development of the BECEREN tool (see also Table 3).

**Emission data missing or available from external source presented in the BECEREN tool.

The results from an evaluation in BECEREN are presented as shown in *Table 2*. In addition to the table, there are also graphs and diagrams visualizing the results (see *Section 5* for more details).

Table 2: Output table from the BECEREN tool, all square meters refer to Heated Floor Area (HFA).

	Energy	Emissions	Costs		Investment			
	Reduction in	Greenhouse gas emissions	Energy	Main-	Total	Positive	Pay	Investm

	energy use		Material production	Mtrl. prod.+ operation energy		tenance		cash flow	back time	ent per energy saving
	kWh/m ² , yr	%	kgCO ₂ e/m ² , yr	kgCO ₂ e/m ² , yr	€/m ² ,yr	€/m ² ,yr	€	Year	Year	€/kWh
Measure 1										
Measure 2										
etc.										
Final perf.										

To ensure the transparency of all calculations within the BECEREN tool all equations, fixed parameters, and detailed information about material requirement, emission data, and investment cost for each measure are available to the user, who also has the ability to change them.

2.3 Operational energy use calculation in BECEREN

In the BECEREN tool, transmission losses are calculated based on the size and performance of the building envelope, i.e. U-values (W/m², K), monthly mean temperature for the location, and average indoor temperature. Ventilation losses are based on the air change rate and temperature difference between monthly mean temperature indoors and outdoors. Internal gains such as heat from occupants and electrical equipment are added as recommended default values per square meter [22]. The same procedure is used for domestic hot water. The household energy use and the behavior of the tenants are assumed to be the same before and after a performed measure (i.e., no rebound effects are taken into account in the tool).

Connected to the BECEREN tool is a separate Excel-tool called SITIS (Solar Irradiation Towards Inclined Surfaces) for calculation of insolation. Data for insolation is based on a computational model called Strång [23] developed at the Swedish Metrological and Hydrological Institute (SMHI). The model calculates direct and global solar irradiation on a horizontal surface (11x11 km) for an arbitrary site in northern Europe based on solar irradiation data from 1999 onwards. SITIS uses these values to calculate irradiation on any given inclined surface, which is done by using empirical correlations between solar altitude and irradiation developed by Brown and Isfält [24] and Pleijel [25]. In the BECEREN tool, monthly average values from 10 years of insolation calculated by SITIS have been used. The results are given as direct and diffuse insolation for a vertical surface (1x1 m) oriented in the four cardinals. This has been done for 10 different locations in Sweden and these are included in the BECEREN tool, and more locations can easily be added.

One important issue is what magnitude of error these types of simplified energy calculation procedures cause compared with dynamic simulations. For this reason, the energy calculation module in the BECEREN tool was validated against two more sophisticated building simulation software packages, in this case VIP-Energy (version 2.1.2) [26] and IDA ICE (version 4.61) [27]. Both VIP-Energy and IDA ICE perform dynamic simulations and have been validated against IEA, ASHRAE, and CEN-standards [28-29]. The validation of the BECEREN tool was done by simulating two fictitious typical Swedish residential buildings representing the building codes of the 1950s and the 1970s in each of the software packages. For further details about the validation of the BECEREN tool, see *Appendix A—Supplementary Information*.

2.4 Calculation of GHG emissions with BECEREN

In the BECEREN tool, calculation of GHG emissions over the life cycle encompasses the product stage and the use stage. These life cycle stages are, in most published LCAs of case study buildings, the dominant contributor to climate change and energy use over the building life cycle [6, 9, 30]. The calculations of GHG emissions in the tool are divided into embodied emissions and emissions related to energy use for building operation respectively.

Embodied GHG emissions are defined in the BECEREN tool as encompassing the CEN 15978 standard [31] modules A1-A3 (product stage) only. In order to calculate the embodied GHG emissions for measures included in BECEREN (see *Table 3*), it was necessary to establish an inventory process for material production. First, a reference unit was established for each measure, as shown in *Table 3*. With reference units defined, the inventory of material requirements for each measure could then be established with respect to this unit. In the case of envelope measures, this inventory process was done by thoroughly measuring and calculating material requirements from the description of measures in either the Swedish industry standard reference manual for refurbishment measures [32] or the Swedish industry standard reference manual for heating, ventilation, and air conditioning systems [33]. Material composition of specific products occurring in the standard reference manuals was requisitioned from any standard product.

Global warming potential (GWP) from material production for each measure in *Table 3* was calculated by matching the material inventories for each measure with relevant material production processes in the Ecoinvent database, v2.2 [34]. GWP for a 100-year perspective was calculated using the CML 2 baseline 2000 v2.05 impact assessment method [35], and the

analysis was made as a cradle-to-gate analysis. Detailed information about material requirements and related GWP are included in the BECEREN tool as well as embodied GHG emissions and estimated service life of each measure. The user has the ability to change all such values if more adequate data is available. The average annual embodied GHG emissions from one measure are derived by dividing the total embodied GHG emissions by the estimated service lifetime of the measure.

Table 3: Description of renovation measures included in the BECEREN tool for which embodied GHG emissions have been calculated for the development of the tool. The default value for estimated service life are based on a government-commissioned survey of the entire Swedish building stock, known as BETSI (Buildings' Energy, Technical Status and Indoor environmental quality) [36]; however, if the tool user has other values for service lifetimes, these can easily be changed in the BECEREN tool.

Number	Name of measure	Description of measure	Estimated service life [years]	Reference unit for calculations
1	Ext. wall 1 – 70 mm	Additional insulation on outer side of exterior walls of wooden framework. 70 mm mineral wool boards with wooden façade.	40	m ² External walls
2	Ext. wall 2 – 120 mm	Additional insulation on outer side of exterior walls of concrete framework. 120 mm mineral wool boards with stucco façade.	40	m ² External walls
3	Ext. wall 3 – 150 mm	Additional insulation on outer side of exterior walls of light weight concrete framework. 150 mm XPS (extruded polystyrene) boards with stucco façade.	40	m ² External walls
4	Ext. wall 4 – 200 mm	Additional insulation on outer side of exterior walls of sandwich (concrete/insulation/concrete) framework. 200 mm XPS boards with stucco façade.	40	m ² External walls
5	Basement wall 1 – 70 mm	Additional insulation on outer side of basement walls below ground, 70 mm XPS boards.	40	m ² Basement walls below ground
6	Foundation 1 – 200 mm	Removal of concrete slab between supporting walls, application of 200 mm XPS boards and new concrete slab 100 mm.	40	m ² Foundation
7	Roof 1 – 100 mm	100 mm mineral wool board applied to the upper side of light weight concrete roof and new waterproofing.	40	m ² Roof
8	Roof 2 – 200 mm	Additional 200 mm loose mineral wool applied to the upper side of attic concrete slab.	40	m ² Roof
9	Roof 3 – 400 mm	Additional 400 mm loose mineral wool applied to the upper side of attic concrete slab.	40	m ² Roof
10	Window 1 – U=1,2	Change whole window to window with U-value = 1.2 W/m ² K, painted wooden frame.	40	m ² Window area
11	Window 2 – U=1,1	Change whole window to window with U-value = 1.1 W/m ² K, wooden frame with exterior cladding of aluminum.	40	m ² Window area
12	Window 3 - Renovation	Change inner pane in a two pane window to an insulated glass unit (U-value = 2.0 W/m ² K), exterior cladding of aluminum on existing frame.	40	m ² Window area
13	Door 1 – Door wood	Change whole front door to front door with U-value = 0.9 W/m ² K, wooden door with side-lite.	40	m ² Front door area
14	Door 2 – Door aluminum	Change whole front door to front door with U-value = 2.0 W/m ² K, aluminum and glass construction.	40	m ² Front door area
15	Door 3 – Balcony door wood	Change whole balcony door to balcony door with U-value = 1.2 W/m ² K, painted wooden frame.	40	m ² Balcony door area
16	Door 4 – Balcony door aluminum	Change whole balcony door to balcony door with U-value = 1.1 W/m ² K, wooden frame with exterior cladding of aluminum.	40	m ² Balcony door area
17	Ventilation 1 – Central AHU	Install mechanical supply/exhaust ventilation with exhaust air heat recovery (EAHR) in building previously with exhaust air ventilation. Central air	20	m ² (HFA)

		handling unit (AHU) for whole building with temperature-based recovery efficiency of at least 80%. Air flow of 0.35 l/s,m ² heated floor area (HFA).		
18	Ventilation 2 – Decentralized AHU	Install mechanical supply/exhaust ventilation with EAHR in building previously with exhaust air ventilation. Decentralized AHU (one in each apartment) with temperature-based recovery efficiency at least 80%. Air flow of 0.35 l/s,m ² (HFA).	20	m ² (HFA)
19	Ventilation 3 – EX-HP	Install exhaust air heat pump for heat recovery in building previously with exhaust air ventilation. Air flow of 0.35 l/s,m ² (HFA).	20	m ² (HFA)
20	Solar Collector system	Install solar collector system with the ability to deliver heat for both heating purposes and domestic hot water.	20*	m ² Collector area
21	Photovoltaic (PV) cell system	Install PV-cell system connected to grid.	20*	m ² PV-cell area

*Assumed value.

The BECEREN tool also considers the GHG emissions from operational energy use. It is possible to select from a list of different energy sources and production mixes, including both heat and electricity supplier. The environmental performance from district heating can vary greatly from one year to another depending on the fuel used, meaning that emissions data from a district heating system rapidly becomes outdated. Since the BECEREN tool is not regularly updated with new emissions data, it is instead possible for the user to insert other values for a specific building or location.

2.5 LCC calculations with BECEREN

Data about investment cost for each improvement measure have been gathered and compiled from the Swedish industry standard reference manuals [32-33]. LCC calculations in BECEREN are based on Net Present Value (NPV) [37], and the results are displayed as time to positive cash flow, payback time, and investment cost per energy saving. The purpose of the application of LCC in this tool was to present results in a way that decision-makers are used to but at the same time to initiate and support a discussion about profitability and what parameters affect it.

The economical evaluation in the BECEREN tool is done by the relation between the average yearly energy costs before and after performing measures during a 50-year period (T). Investment cost (I) and estimated service life (t) of each measure are available in the tool. It is assumed that when the estimated service life has expired, a re-investment is done for the same measure. It is assumed that investment costs and maintenance costs related to a specific measure increase through inflation. Furthermore, it is assumed that the investment is financed by loans. Discount rate and installments are included in the NPV. It is assumed that installments are equally distributed during the estimated service life of the specific measure.

With the BECEREN tool it is possible to choose the annual change in energy prices in real terms. The NPV for future annual energy cost is calculated with this number. The tool also allows for the possibility to test how different annual energy price development rates and discount rates affect the outcome of the LCC.

3 Outline of sustainability targets in a Swedish context

According to an interview study among Swedish property owners reported by Olsson *et al.* [5], environmental targets in renovation projects were not common and if they existed, they tended to be modest in terms of ambitions compared to, for instance, long-term energy reduction targets at the societal level. Setting achievable but ambitious environmental targets for a renovation project is not a straightforward task. Therefore, we here propose the idea of sustainability targets as a means to operationalize sustainability targets for society at large. The starting point for such targets is based on works such as *planetary boundaries* by Steffen *et al.* [38] and Raworth's *A safe and just operating space for humanity* [39] that offer a strong sustainability discourse, as well as the following views on sustainable development of the built environment taken up by Wangel *et al.* [40]: "Sustainable development is about achieving human well-being and social justice within ecological limitations"; "Social and natural capital are not exchangeable"; and "Ecological limitations are real." However, to move from such overarching principles to practice requires further elaboration. First, formulations like "human wellbeing," "social justice," and "ecological limitations" need to be better defined. One useful way to search for more operationalized definitions is to rely on consensus documents of significance. Examples of relevant consensus documents include the *Sustainable Development Goals* of the United Nations [41] and the work within EU [42-43]. In the Swedish context, the 16 national Environmental Quality Objectives (EQOs) also provide such a starting point [44].

In the research project to which the work presented in this paper belongs, the selection of relevant sustainability aspects based on principles and ideas taken up above is further elaborated. However in this paper, we continue directly onto the task to elaborate target levels for three of these selected aspects, which are the environmental aspects covered by the BECEREN tool; energy use for building operation, GHG emissions due to total energy use for building operation, and embodied GHG emissions due to the production of construction materials. Proposed target levels in the Swedish context for the above mentioned aspects are

shown in *Table 4* and how they are derived are described briefly in the following subsections. These target levels may then be used as a starting point for elaborating project-specific target levels in renovation projects, with help of a tool like BECEREN.

Table 4: Proposed sustainability target levels, in the Swedish context, for three important aspects.

Aspect	Target level	Unit
GHG emissions due to total energy use for building operation (total energy includes operational energy plus domestic energy)	1.3	kgCO ₂ e/m ² (HFA),year
Energy use for building operation	62	kWh/m ² (HFA),year
Embodied GHG emissions due to the production of construction materials	Derived by the expression: $0.01 \cdot (E_B - E_A) + 0.10,$ Where E_B is the energy use for the original building and E_A is the energy use after performed measures. 0.01 is a conversion factor.	kgCO ₂ e/m ² (HFA),year

3.1 Sustainability target for GHG emissions due to total energy use for building operation

The proposed target level for GHG emissions due to total operational energy use shown in *Table 4* is based on the statement by the Swedish Environmental Protection Agency [45] implying that the sector “Residential & Tertiary” should reduce its GHG emissions by 90% by 2050 compared to the baseline year 1990. A similar statement is made by the EU implying that the sector “Residential & Tertiary” needs to reduce GHG emissions by 88-91% by 2050, compared with 1990 [46]. With these statements in mind, we used statistics from the Swedish authorities and calculated the proposed target level. However, the statistics are not comprehensive enough, which means that assumptions and simplifications have to be made. Emissions of CO₂ from the Swedish “Residential & Tertiary” sector were about 11.6 Mton in 1990 [47]. The total number of heated floor area (HFA) in 1995 was about 598 million square meters [48]. New constructed dwellings during the period 1995 – 2014 correspond to about 1.9 million square meters per year [49-50]. In addition, about 2.8 million square meters of commercial premises are built every year, which is the average for 1998 – 2014 [51]. With the assumption that the buildings stock grows at the same rate as in the past 15 – 20 years, the total number of HFA in 2050 will be approximately 858 million square meters. This will then yield a target level of about 1.3 kgCO₂e/m²(HFA),yr.

3.2 Sustainability target for operational energy use

Even though renewable energy sources are used for operational energy use, this is not a reason to use excessive energy. Energy efficiency has come to be recognized as a major

energy resource; in 2010 energy use avoided by IEA countries was larger than any other single supply-side resource [52]. Therefore, we still find it important to have a target for operational energy use even though this is indirectly included in the overarching target for GHG emissions due to total energy use for building operation. The proposed target for energy use for building operation (bought energy) is shown in *Table 4*. Bought energy is a notion used in Swedish regulations for the energy use of a building where domestic electricity is not included [53]. The operational energy target is based on the EU Energy Efficiency Directive [54], which stipulates that member states should establish a long-term strategy beyond 2020 with the aim of improving the energy performance of their building stock. In line with this, the Swedish Government has decided that *“total energy use per unit heated floor area of residential and commercial premises should be reduced by 20% by 2020 and by 50% by 2050 compared to 1995”* [55]. This statement together with statistics from the Swedish authorities was used to calculate the proposed target level. However, the statistics are not comprehensive enough, which means that assumptions and simplifications have to be made. The estimated operational energy use in the Swedish “Residential & Tertiary” sector was about 106 TWh in year 1995 [56]. With the same assumptions for HFA as deliberated in the previous section, the target level would be about 62 kWh/m²(HFA),yr.

3.3 Target level for embodied GHG emissions due to production of materials

When formulating targets for embodied GHG emissions for renovation purposes, it is necessary to consider the energy performance before and after. A target needs to relate to the amount of material used for reduction of operational energy use. Therefore, we propose an expression for the calculation of the target level (see *Table 4*) related to the operational energy use of the normalized original building (E_B) and the operational energy use after performed improvements (E_A) in kWh/m²(HFA),yr. The proposed expression is based on the linear regression of measures plotted in a diagram with reduction of operational energy use on the x-axis and embodied GHG emissions on the y-axis. Measures plotted in the diagram are a selection of measures included in the BECEREN tool applied to the case study building.

Further details about these targets are currently described in a forthcoming report [57] where other aspects relevant to sustainable renovation are also discussed and targets are formulated for the Swedish context. Examples of other target areas are: indoor environmental quality, use of resources, and waste management.

4 Description of the case study building

The analytical process of establishing environmental targets and a working direction in the early stages of a renovation process is illustrated by a case study on a residential building from 1961. This particular building is owned by one of the companies in the project reference group and was chosen because it is a typical multifamily building, and approximately one fifth of the residential buildings in Sweden were built around this time [58]. The building is located in Ljusdal in the middle of Sweden. The building comprises 528 m² of lettable area, distributed among seven apartments, with a total HFA of 720 m². It is a four-story building where the first floor is a semi-basement floor and the top floor is an attic (see *Figure 2* and *Figure 3*).

Figure 2: Case study building seen from the south west.

Figure 3: Case study building seen from the north.

The building is more or less in its original design from the year of construction except that all windows and balcony doors were changed in 2009. The new windows are three-pane insulated glass with a wooden frame. The foundation is made of reinforced concrete and the external walls consist of 0.35 m light weight concrete with plaster. The building is connected to the local district heating grid of Ljusdal, and heat within the building is distributed with a hot water radiator system. The ventilation system is based on natural ventilation. The building was investigated on site; for detailed input data about the case study building, see *Table 5*. Altogether the total building operational energy is 172 kWh/m²(HFA),yr. The average value of delivered heat during June, July, and August was used to estimate what part of heating demand was being used for domestic hot water on an annual basis with the assumption that no or very little energy was needed for heating purposes during this period.

Table 5: Data on the case study building used for the BECEREN tool calculations.

Basic building data	
Country / Place	Sweden / Ljusdal
Year of construction	1961
Principal use	Residential
Total heated floor area (HFA)	720 m ²
No. of floors	4
Type of ventilation system	Natural
External heat source	District heating – Ljusdal
External electricity source	Nordic electricity mix
Optional building data	
No. of occupants	15
Internal heat gain from occupants	0.97 W/m ² (HFA)
Internal heat gain from equipment	2.40 W/m ² (HFA)
Average Indoor temperature (winter time)	21.5°C
Average ventilation air flow	0.24 liter/m ² (HFA)/sec

Average air leakage flow (at dP ±50 Pa)	0.03 liter/m²(HFA)/sec
Total window area incl. frame	87.9 m²
Window area, north	21.0 m²
Window area, east	13.8 m²
Window area, south	38.5 m²
Window area, west	14.6 m²
Fraction of glass	80%
Solar heat gain coefficient (g-factor of glass)	0.66
Door area incl. frame (main entrance and balcony)	18.8 m²
Building perimeter (inside)	57.1 m
External wall area (excl. windows and doors)	330.3 m²
Area of roof	190.0 m²
Area of foundation	195.8 m²
Basement wall area (towards ground)	44.2 m²
Ceiling height	2.74 m
U-value, outer wall	0.45 W/m²,K
U-value, roof	0.35 W/m²,K
U-value, foundation	0.60 W/m²,K
U-value, basement wall	0.60 W/m²,K
U-value, windows	1.70 W/m²,K
U-value, doors	1.80 W/m²,K
Thermal bridges (% of overall U-value)	7.0%
Anticipated life time	50 years
Building Thermal weight (light/medium/heavy)	Heavy
Building gross volume	1793 m³
Monitored energy use 2014	
Heating demand (corrected for a standard year)	70.8 MWh/year
Building operational electricity	15.1 MWh/year
Domestic hot water	37.6 MWh/year
Domestic electricity	21.6 MWh/year
Energy prices	
District heating (VAT excl.)	5.5 €/kWh
Electricity (VAT excl.)	9.5 €/kWh
GHG emission from energy supply	
District heating (Ljusdal)	0.033 kgCO ₂ e/kWh
Electricity (Nordic electricity residual mix)	0.344 kgCO ₂ e/kWh

5 Case study illustration

This case study was used to illustrate a procedure for facilitating project-specific target setting and exploring potential renovation and improvement measures, in an early project design stage, to support consideration of long-term sustainability targets. The procedure consists of the following steps:

1. Establish a baseline building model for normalization of energy use;
2. Choose measures for reduction of operational energy use to achieve the sustainability target;
3. Check achievement of climate targets (GHG emissions) and see if additional measures can be done to reduce the impact;

4. Economic assessment of chosen measures to establish potential target levels for the renovation project; and
5. Establish a long-term plan of action to achieve the sustainability target.

The stepwise procedure for the case study building is described in the following subsections

5.1 Normalization of the energy use

First, we entered the building data listed from *Table 5* in the BECEREN tool. The tool calculated the energy use for building operation (bought energy) to be 178 kWh/m²(HFA),yr. The difference between calculated and monitored energy use was about 3%, which confirmed that input values were fairly correct. As seen in *Table 5*, the ventilation air flow was below the required air flow rate of 0.35 liter/m²(HFA),sec stipulated by the Public Health Agency of Sweden [59] for dwellings. Before further analysis of improvement options, the building calculations needed to be normalized. This meant increasing the ventilation air flow rate to meet the regulation requirements. During the on-site investigation, measurements showed that the indoor temperature varied and was also slightly higher than normal. A sufficient average indoor temperature if no draft is present should be 20°C during winter [60] instead of 21.5°C, which was the case (cf. *Table 5*). With these new preconditions, the calculated bought energy use became 180 kWh/m²(HFA),yr. Additionally, domestic electricity use was added as a normal value of 30 kWh/m²(HFA),yr [22]. By implementing these changes, we created a hypothetical building with the same shape as the case study building but adjusted to a level when current building regulations were achieved. There were several reasons for this. A building might for instance not comply with current regulations concerning, e.g., ventilation and thermal comfort, which is common for older buildings. The use of the building might be extreme in some respect, for instance, either too low or too high an indoor temperature, which affects the energy use significantly. The number of tenants per square meter might also be other than normal, which affects the internal heat gains from people and devices. Such often temporary deviations from normal use and performance can be argued not to be the basis for selection of long-term renovation measures. Comparability with similar buildings would also be lost. However, in consultation with the property owner of the case study building, it was decided not to normalize the use of domestic hot water in this specific case, given this specific building's very low turn-over of tenants. How to normalize the measured energy use in a specific building, before evaluation of improvements, needs to be handled on a case by case basis depending on specific preconditions.

5.2 Choose measures to achieve the sustainability target level for operational energy use

With the normalized starting point, along with the three targets elaborated upon in *Section 3*, the procedure for evaluating improvement measures could start. The aim of the evaluation procedure was to achieve the sustainability targets. If it were shown that the targets were out of reach, what would then be achievable but ambitious performance levels for a specific renovation project or building?

The evaluation procedure starts with choosing improvements until the sustainability target for energy use is achieved, starting with measures reducing heat loss. This is because energy use is something that a property owner has significant influence over, and is also a performance indicator that most property owners currently can relate to, as opposed to GHG emission targets. The GHG emission targets are continuously monitored by the tool as the testing of improvement options progress. In the BECEREN tool, the user can view the energy loss for different parts of the building as a bar diagram; in *Figure 4*, this is shown for the normalized case study building.

Figure 4: Energy loss for different parts of the case study building, as presented in the BECEREN tool.

Following *Figure 4*, evaluation starts with measures that recover heat from exhaust air. Next are measures to reduce domestic hot water usage, which is the second largest source of energy loss for the building. The third largest source of energy loss is related to domestic electricity;

however, this is not included in the Swedish regulation concept of bought energy [53]. Therefore, we omitted dealing with improvement measures related to this source of energy loss for the purpose of the exercise presented here. However, this is not to say that it is unimportant. The evaluation procedure continues with the fourth largest energy loss, which is loss through windows, and so on. *Table 6* shows the calculated results from the starting point of the original building conditions and with selected renovation improvement measures.

The bar diagram presented in BECEREN (see *Figure 5*) now shows the estimated performance of the building after selected improvements needed to potentially reduce operational energy use to the proposed sustainability target level. Included in *Figure 5* is also the estimated performance of the original building before improvements. From *Figure 5*, it can be seen that the dominant sources of energy loss after selected improvements are domestic hot water and building operation electricity (domestic electricity excluded).

Figure 5: Calculated energy loss for different parts of the building, before and after improvements; diagram presented in the BECEREN tool.

Table 6 presents numbers for each specific measure as executed separately. The final impact on the performance of the building from executing all measures as one renovation package is

presented in the second row from the bottom of *Table 6*. The final reduction in operational energy use is not the sum of all individual measures since different measures interact and affect the overall heat demand for the building together with the internal heat gains. The starting point for the case study building is presented in the last row of *Table 6*. The table does not include domestic electricity, which is assumed to remain at 30 kWh/m²(HFA),yr.

Table 6: Results from the evaluation of measures for the case study building, domestic electricity not included. All square meters refer to Heated Floor Area (HFA) of the building.

	Energy		Emissions		Costs		Investment			
	Reduction in energy use		Greenhouse gas emissions		Energy	Main-tenance	Total	Positive cash flow	Pay-back time	Investment per energy saving
			Material production	Mtrl. prod. + operation energy						
	kWh/m ² , yr	%	kgCO ₂ e/m ² ,yr	kgCO ₂ e/m ² ,yr	€/m ² ,yr	€/m ² ,yr	€	Year	Year	€/kWh
Measure 1	46.5	25.8	0.40	-0.20	-2.44	0.20	31,973	11	20	0.04
Measure 2	15.7	8.7	0.30	-0.22	-0.86	0.00	10,800	0	17	0.05
Measure 3	11.6	6.4	0.47	0.09	-0.64	0.00	51,261	51	112	0.37
Measure 4	19.4	10.8	0.09	-0.55	-1.07	0.00	30,324	21	39	0.06
Measure 5	9.9	5.5	0.30	-0.02	-0.54	0.00	35,341	47	90	0.14
Measure 6	8.6	4.8	0.06	-0.22	-0.47	0.00	2,689	0	8	0.01
Measure 7	1.4	0.8	0.01	-0.03	-0.08	0.00	11,140	51	205	0.31
Measure 8	12.5	6.9	0.14	-0.28	-0.69	0.00	11,792	20	24	0.07
Measure 9	2.3	1.3	0.83	0.05	-0.22	0.00	4,388	26	28	0.13
Final perf.	62.2	65.5	2.6	11.4	4.3	0.2	189,707	34	42	1.0
<i>Start. point</i>	180.1	-	-	12.5	10.6	-	-	-	-	-

Measure 1: Installation of mechanical exhaust and supply air ventilation with central air handling unit with heat recovery (measure 17 in Table 3).

Measure 2: Installation of waste water heat exchanger and installation of low flow fixtures in kitchen and bath (measure not included in Table 3).

Measure 3: Change of windows, U-value 1.1 W/m²,K (measure 11 in Table 11).

Measure 4: Additional insulation on outside of exterior wall, 200 mm XPS board (measure 4 in Table 3).

Measure 5: Additional insulation of basement floor between supporting walls, 200 mm XPS board (measure 6 in Table 3).

Measure 6: Additional insulation of attic, 400 mm loose mineral wool (measure 9 in Table 3).

Measure 7: Additional insulation on outer side of basement walls below ground, 70 mm XPS boards (measure 5 in Table 3).

Measure 8: Installation of solar collector system, 20 m² (measure 20 in Table 3).

Measure 9: Installation of PV-cell system, 15 m² (measure 21 in Table 3).

The column “Mtrl. prod. + operation energy” in *Table 6* shows the combined impact from increased CO₂e emissions due to material production (which is shown in the column to the left) and reduced CO₂e emission due to reduced operational energy use. Notable here is that the lack of negative sign before the values for measures 3 and 9 means that they actually cause more CO₂e emissions than they save. The number of years related to each measure is the same as estimated service life shown in *Table 3*. The total influence from all improvements chosen are enough to reach the suggested target of 62 kWh/m²(HFA),yr for operational energy use.

5.3 Check fulfillment of climate targets (GHG emissions)

The BECEREN tool also presents a graph of the energy use, energy cost, and GHG emissions for all selected measures. For the case study building, this is presented in *Figure 6*. The figure gives an overview of how each individual measure may influence the performance of the building.

Figure 6: Graphical presentation for measures tested on the case study building, domestic electricity not included.

Figure 6 shows that the graphs for energy use and energy cost more or less follow each other, which were expected. However, looking at the graph representing the total GHG emissions (i.e., the sum of embodied GHG emissions and operational energy GHG emissions after improvement), one can see that this does not decline much at all. This is due to the fact that the district heating system in Ljusdal has a high share of renewable fuels, which means that reduction in heating demand has a low influence on GHG emissions. *Table 7* shows the proposed sustainability targets and achieved values for the case study. Looking at *Table 7*, it is clear that sustainability targets for GHG emissions due to total energy use for building operation and embodied GHG emissions are far from achieved and would therefore require further exploration of improvements.

Table 7: Proposed sustainability targets together with achieved values for the case study building.

Aspect	Target level	Achieved level for case study building	Unit
Energy use for building operation	62	62	kWh/m ² (HFA),yr.
GHG emissions due to total energy use for building operation	1.3	19.1*	KgCO ₂ e/m ² (HFA),yr.
Embodied GHG emissions due to the production of materials	1.3	2.6	KgCO ₂ e/m ² (HFA),yr.

*Including domestic electricity, assumed to 30 kWh/m²(HFA),yr and Nordic electricity residual mix 0.344 kgCO₂e/kWh.

Improvements could be made to reduce the GHG emissions of the case study building. By changing the electricity mix to one with higher share of renewable fuels, the achieved levels for the case study building could be lower. If changing to an electricity mix with 0.1 kgCO₂e/kWh, the achieved level becomes 6.5 kgCO₂e/m²(HFA),yr for GHG emissions due to total energy use for building operation (cf. *Table 7*). However, this was not something that was further explored in the case study.

5.4 Economic assessment of suggested measures

For each of the different parts considered in *Figure 4*, there are often several alternative measures to choose from in the same category in the BECEREN tool. In this case study, selection was done by choosing the alternative with the shortest time to positive cash flow. The default settings for economic analysis are annual energy price change rate +3% and discount rate of 5%. Not all improvement measures are profitable with the default settings. Taken together as a renovation package, it would take 34 years for all nine improvements from *Table 6* reach a positive cash flow. By ranking the improvements in *Table 6* by investment cost per energy saving, it is possible to add measures one by one, starting with the one with lowest investment cost per energy saving, until the desired time to positive cash flow is exceeded (e.g., 10 years). Doing this, and at the same time elaborating on a more favorable economic scenario, will produce a plan of action for a forthcoming renovation project.

With annual energy price change rate of +3% and a discount rate of 4%, improvement measures 6, 1, 2, and 4 (cf. *Table 6*) will yield a time to positive cash flow of about 9 years. Evaluations in the BECEREN tool showed that none of the other measures could be included in this economic scenario if the time to positive cash flow was 10 years or less; in that case, other economic scenarios should then be considered. However, for the purpose of the exercise

presented here, this was not pursued further. If measures 6, 1, 2, and 4 are to be carried out in a forthcoming renovation project, estimations in the BECEREN tool yield that the target levels for the project could be 90 kWh/m²(HFA),yr for operational energy use, 20 kgCO₂e/m²(HFA),yr for GHG emissions due to total energy use for building operation, and 1.0 kgCO₂e/m²(HFA),yr for embodied GHG emissions.

5.5 Establish a long-term plan for sustainability target achievement

The nine measures listed in *Table 6* could be seen as a long-term plan of action to reach the sustainability target for operational energy use. These improvement measures could be implemented in a number of renovation projects until year 2050. The forthcoming renovation project could be seen as a first step of several renovation steps to reach the sustainability targets for the building. A possible long-term plan of action for implementation of improvement measures regarding operational energy use in the case study illustration is shown in *Figure 7*. Each renovation step in *Figure 7* is connected with specific improvement measures from *Table 6*, step 1 includes measures 1, 2, 4, and 6, step 2 includes measures 5, 8, and 9, and step 3 includes measures 3 and 7. This long-term plan of action should also include actions to reduce GHG emissions, for instance, by changing energy supplier. However, this was not something that was further developed in the case study.

Figure 7: Long-term plan of action regarding operational energy use for the case study building; each step can be seen as a renovation project relating to a specific set of measures to reach the sustainability target.

6 Discussion and conclusion

The case study illustration in the previous section illustrates how the BECEREN tool can be applied to identify ambitious but achievable target levels for a specific project that also relate to overarching sustainability targets for the built environment. In addition, it identifies indicative improvements necessary for the achievement of such targets, which could be further investigated in later renovation project stages or future renovation projects. Finally, the tool also enables consideration of embodied GHG emissions and LCC results.

In this paper, we have introduced the notion of sustainability targets for renovation projects based on societal goals and suggested having an overarching sustainability target regarding GHG emissions due to total energy use for building operation. The GHG emissions are interconnected with the use of energy, and the reduction of GHG emissions from energy use is in turn interconnected with the performance of the energy supplier. Therefore, when prioritizing improvement measures, it is reasonable to start looking at energy demand in relation to a sustainability target for energy use. With the help of the BECEREN tool, the achievement of a GHG emissions target can be controlled after testing each relevant improvement option. In its current state, the BECEREN tool is applicable only to dwellings in Swedish conditions. However, the evaluation procedure is applicable to all buildings.

The case study illustration implies that it may be possible to reach the proposed sustainability target for operational energy use for this normalized case study building by implementing improvements according to *Table 6*. These improvements are not to be seen as the optimum set of improvements, but rather a number of measures that indicate a combination of measures that could achieve the sustainability target for energy use. These measures then have to be further developed and investigated in later project stages. Furthermore, the analysis does not take rebound effects into account.

The target for embodied GHG emissions seems not to be easy to reach and the target level for GHG emissions from total energy use for building operation seems far from achieved despite the fact that the energy demand was reduced significantly (cf. *Table 7*). In the case study illustration, emissions data was used for current production mixes of the district heating system that the case study building is connected to, as well as the Nordic electricity residual mix. Since these mixes are currently based on certain shares of non-renewable fuels, they have a large impact on the performance of a building, and in the case study this especially applies for electricity. This implies that far-reaching energy efficiency targets at the project

level are often not enough to reach similar long-term climate targets on a societal level. Displaying the discrepancy between what could be achieved in terms of GHG emissions due to energy use in buildings and what is actually needed to reach long-term societal targets can enable a discussion about different actors' potential range of action. The need for additional climate policy measures for the energy system becomes clear, as well as the need for setting up long-term action plans within property owner organizations. Nevertheless, even though the application of the BECEREN tool to the case study building reveals a large gap between the sustainability target level and the potential to reach it for this particular building, it is probable that the share of non-renewable fuels in the Swedish energy system as a whole will decrease in the future. This means that the possibilities of reaching the sustainability target level for GHG emissions from operational energy use will increase in the future. The tool does not include the option to dynamically model future changes in the energy system; however, it is easy to test how different emission factors of supplied energy influence the result. It should also be noted that the BECEREN assessment does not include modeling of potential future reduction of heating degree days due to climate change and that this issue might affect the suggested choices of actions.

To reach the proposed sustainability target level for operational energy use in the case study, the embodied GHG emissions contribute an extra $2.6 \text{ kgCO}_2\text{e/m}^2(\text{HFA})\text{,yr}$, which is about 12% of the total GHG emissions (including impact from domestic electricity). Similar results regarding the share of embodied GHG emissions for renovation have also been shown in previous studies [6, 9, 61]. This constitutes a relatively small but not insignificant part, which suggests that it is relevant to consider embodied emissions not only in new building but also in renovation projects. In the case study example, the suggested target level for embodied GHG emissions seems not to have been reached. There are two measures where embodied GHG emissions are higher than the reduction due to operational energy saving (cf. measure 3 and 9 in *Table 6*), these two measures are window replacement and installation of PV-cells. In decision making in renovation processes, practitioners and policymakers should therefore be aware that it may be important to take material production for such measures into account in order to decrease GHG emissions. Furthermore, insulating materials have relatively high embodied emissions, which would indicate a need for technological development in this area in order to produce these with less GHG emissions.

Choosing what measures to evaluate can be altered in many ways. Working with the case illustration, our focus was to reduce energy demand to the proposed sustainability

performance level. Needed improvements could be performed as one complete renovation package or as several smaller renovation steps distributed in time up through 2050. The BECEREN tool is designed to facilitate the establishment of such long-term plans of action and to initiate discussions of “distance-to-target” in individual projects. By working with the case study building, the initial evaluation procedure was further developed. To summarize, we propose a stepwise procedure for evaluating measures and creating a long-term plan of action as follows:

1. Check if there is abnormally high energy use or comfort requirements not fulfilled for the building and take actions;
2. Choose improvements until the sustainability target for energy use is achieved, using default settings for economic calculations, and then start evaluating measures to reduce heat loss, ensure efficient electricity use, and choose an energy source;
3. Rank the potential measures by investment cost per energy saving (€/kWh) and determine the profitability requirements, with some margin, in terms of years to positive cash flow;
4. Choose measures one by one, starting with the lowest investment cost per energy saving from step 2 until the requirement for years to positive cash flow is exceeded;
5. Evaluate how the time to positive cash flow changes by changing the default settings (i.e., energy price development rate and discount rate), evaluate different future scenarios, and check if additional measures (continue with measures excluded in step 4) can be included in the list of actions with a more favorable economic scenario;
6. Consider alternative funding (e.g., building extensions to increase lettable area or increases in rent) to include additional measures;
7. Check that the sustainability targets for GHG emissions are achieved, and if not, evaluate whether it is possible to change the energy source to one with a better production mix; and
8. Establish a long-term plan for achievement of the sustainability targets.

The BECEREN tool along with the suggested step-by-step evaluation approach provides an effective way to evaluate various potential improvement options in the early project stages. However, it is not necessary to use the BECEREN tool, as other tools or a combination of tools with the same purpose as the BECEREN tool can be used together with the evaluation procedure. With the ability to vary economic parameters such as future energy price development rates and discount rates, another important discussion may also be facilitated

regarding relevant levels of these parameters when calculating cost-efficiency at project level. It can be argued that required profitability for long-term strategic measures should be lower than for short-term investments, but the common approach in practice is to use the same discount rate for evaluating both types of investments [62].

The performance level of the two sustainability targets, operational energy use and GHG emissions due to total energy use for building operation (elaborated on in *Section 3*), are based on average values including the whole building stock in Sweden. However, it is not likely that the whole building stock will be renovated to the extent needed; for instance, cultural heritage values make some building envelope measures impossible. The proposed performance level for embodied GHG emissions is based on today's practice and the expression should be further studied by testing additional buildings and measures as well as considering future technology improvements. Considering these facts, sustainability target levels proposed here could be argued to be lower as well as further discussed. However, this provides a good starting point for raising the ambitions of the vast number of current refurbishment projects in Sweden and Europe in relation to climate change mitigation.

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Appendix A—Supplementary Information

Validation of operational energy use calculation

Different suppliers of simulation software have different computational models to simulate entities such as latent heat, heat transfer coefficients, thermal storage, solar irradiation (heat gain through windows), and ground properties. For this reason, the energy calculation module in the BECEREN tool was evaluated against more sophisticated building simulation software packages, in this case VIP-Energy (version 2.1.2) [1] and IDA ICE (version 4.61) [2]. Both VIP-Energy and IDA ICE perform dynamic simulations and have been validated against IEA, ASHRAE, and CEN-standards [3], [4]. The validation of the BECEREN tool was done by simulating three different cases of two fictitious typical Swedish residential buildings representing the building codes of the 1950s and the 1970s in each of the three different software packages. The buildings have different characteristics and are all assumed to be located in Stockholm, Sweden. The 1950s and 1970s buildings are referred to as *Building 1* and *Building 2*, respectively, and input data for the buildings are shown in *Table 8*. The two buildings were simulated as one zone (i.e., one large volume), and this might have affected the simulation results from VIP-Energy and IDA ICE, but this is how the calculation is done in BECEREN.

Table 8: Building data for the two example buildings used to validate BECEREN.

	Building 1 (1950s standard)	Building 2 (1970s standard)
Location	Stockholm	Stockholm
Orientation of building	oriented in east - west	oriented in east - west
Horizontal shading [degrees]	0	0
g-value (g_{glass})	0.380	0.380
ST-value (ST_{glass})	0.304	0.304
Fraction of frame [%]	10	10
Year of construction	1950	1970
Internal length of building [m]	24.0	33.0
Internal width of building [m]	11.0	12.0
Building perimeter [m]	70.0	90.0
No. of floors (above ground level)	3.5	6.0
No. of floors (below ground level)	0.5	0.0
Heated floor area [$\text{m}^2(\text{HFA})$]	1056	2376
Floor height (top -- top) [m]	2.90	2.70
Heated building volume [m^3]	2798.4	5821.2
Type of ventilation system	Mechanical exhaust air	Mechanical exhaust air
Type of heating system	Water based radiator system	Water based radiator system
Indoor air temperature (average in winter time) [$^{\circ}\text{C}$]	21.0	21.0
Air leakage at dP 50 Pa [$\text{l/s,m}^2(A_{\text{envelope}})$]	0.80	0.80
Ventilation air flow [$\text{l/s,m}^2(\text{HFA})$]	0.35	0.35
External wall (excl. Windows & doors) [m^2]		
North	184.4	372.0
East	85.4	144.7

South	174.4	374.0
West	85.4	144.7
Walls toward ground [m²]	92.8	0.0
Window area [m²] (area of glazing)		
North	36.2	87.1
East	16.6	31.7
South	36.2	87.1
West	16.6	31.7
Door area (entrance & Balcony) [m²]		
North	2	26.0
East	0	0.0
South	12	24.0
West	0	0.0
Roof [m²]	264	396.0
Floor/Foundation [m²]	264	396.0
Building thermal weight [light / medium / heavy]	Heavy	Heavy
U-value - walls [W/m²,K]	0.70	0.45
U-value - roof [W/m²,K]	0.50	0.40
U-value - floor/foundation [W/m²,K]	0.30	0.30
U-value - walls towards ground [W/m²,K]	2.00	1.50
U-value - windows [W/m²,K]	2.90	2.90
U-value - doors [W/m²,K]	3.00	2.50
Thermal bridges [% of transmission losses]	10	10
No. of apartments	6	24
No. of occupants	21	48
User electricity [kWh/m²(HFA),yr]	30	30
Share of user electricity to internal gains	70	70
Internal gain from user electricity [W/m²(HFA)]	2.40	2.40

The three cases were: (i) building body without effect of internal gains and insolation, (ii) building body with internal gains but without insolation, and (iii) building body with the effect of both internal gains and insolation. These cases were chosen because it was then possible to see the difference between different computational models when introducing internal gains and solar heat gain through windows. However, most important is that transmission and ventilation losses are similar.

The relative difference between the calculated results for each of the three cases can be seen in *Table 9*, *Table 10*, and *Table 11* for the 1950s and the 1970s buildings, respectively. Results from BECEREN are used as a reference point. IDA ICE and VIP-Energy use different weather data for Stockholm than BECEREN, which among other things is shown in various mean annual temperatures. BECEREN uses 6.30°C, IDA ICE uses 6.65°C, and VIP-Energy uses 7.50°C for mean annual temperature. Differences in mean annual temperature have been compensated for in the following tables.

Table 9: Simulation results without the effect of internal gains and insolation (case i) for Buildings 1 and 2 in relation to calculations in the BECEREN tool.

	Building 1		Building 2	
	VIP-Energy	IDA ICE	VIP-Energy	IDA ICE
Transmission losses	-4.1 %	2.1 %	-0.7 %	3.7 %
Ventilation losses	-0.1 %	-2.4 %	2.7 %	0.4 %
Total heating demand	-3.3 %	2.3 %	0.1 %	2.4 %

Table 10: Simulation results with the effect of internal gains but without insolation (case ii) for Buildings 1 and 2 in relation to calculations in the BECEREN tool.

	Building 1		Building 2	
	VIP-Energy	IDA ICE	VIP-Energy	IDA ICE
Transmission losses	-1.7 %	1.5 %	2.7 %	3.2 %
Ventilation losses	2.1 %	9.8 %	5.8 %	12.8 %
Internal gains (electrical equipment and occupants)	11.5 %	36.7 %	24.4 %	45.4 %
Total heating demand	-6.5 %	-3.0 %	-5.6 %	-4.0 %

Table 11: Simulation results with the effect of internal gains and insolation (case iii) for Buildings 1 and 2 in relation to calculations in the BECEREN tool.

	Building 1		Building 2	
	VIP-Energy	IDA ICE	VIP-Energy	IDA ICE
Transmission losses	4.1 %	1.9 %	11.9 %	3.6 %
Ventilation losses	5.4 %	12.0 %	11.3 %	16.8 %
Internal gains (electrical equipment and occupants)	11.5 %	34.8 %	24.4 %	42.9 %
Solar gain through window	26.6 %	3.1 %	129.9 %	30.2 %
Total heating demand	-4.9 %	-2.8 %	-12.0 %	-5.4 %

As seen in *Table 9*, the congruence between the three software packages is quite good when comparing total heating demand, with the deviation being 3.3% or smaller. Sometimes the dynamic simulation software packages overestimate total heating demand and sometimes underestimate it compared to the BECEREN tool. Overall BECEREN underestimates total heating demand compared to IDA ICE. Compared to VIP-Energy, the BECEREN tool overestimates total energy demand for *Building 1*, and for *Building 2*, it is more or less the same.

When introducing internal gains in the simulations (see *Table 10*), it can be seen that BECEREN underestimates heat from internal gains compared to both VIP-Energy and IDA ICE. IDA ICE gives higher values than VIP-Energy. This is mostly due to the fact that IDA ICE considers latent heat from occupants in a more complex way than VIP-Energy, while

BECEREN does not consider this at all. As evident in *Table 10*, the mutual difference between the various posts becomes large when introducing internal gains. However, the discrepancies in total heating demand still have good congruence. The minimum discrepancy is 3.0% and the maximum is 6.5% when looking at total heating demand for both buildings compared to the results from BECEREN. In both cases, BECEREN slightly overestimates total heating demand for the two buildings.

Looking at *Table 11*, it can be seen that BECEREN underestimates solar heat gain through windows compared to both VIP-Energy and IDA ICE. However, it seems that VIP-Energy greatly overestimates the heat contribution from insolation, both compared to BECEREN and to IDA ICE.

When summing up the tested cases for the two buildings, we would like to argue that BECEREN is accurate enough to perform energy simulations in an early stage of the building process.

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