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Author

Stadler, Michael

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Michael Stadler[1,2,], Markus Groissböck[1,2]
Gonçalo Cardoso [1,3], Chris Marnay[1]

[1] *Ernest Orlando Lawrence Berkeley National Laboratory, One Cyclotron Road, MS: 90-1121, Berkeley, California 94720, USA*

[2] *Center for Energy and innovative Technologies (CET), Doberggasse 9, 3681 Hofamt Priel, Austria*

[3] *Instituto Superior Técnico - Technical University of Lisbon, Portugal*

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Optimizing Distributed Energy Resources and Building Retrofits with the Strategic DER-CAModel

M. Stadler[1,2,*], M. Groissböck[1,2], G. Cardoso[1,3], C. Marnay[1]

[1] *Ernest Orlando Lawrence Berkeley National Laboratory, One Cyclotron Road, MS: 90-1121, Berkeley, California 94720, USA*

[2] *Center for Energy and innovative Technologies (CET), Doberggasse 9, 3681 Hofamt Priel, Austria*

[3] *Instituto Superior Técnico - Technical University of Lisbon, Portugal*

* *Corresponding Author: mstadler@lbl.gov or mstadler@cet.or.at, Tel.: +1.510.486.4929 or +43.(0)664.7390.7185*

Abstract

The pressuring need to reduce the import of fossil fuels as well as the need to dramatically reduce CO_2 emissions in Europe motivated the European Commission (EC) to implement several regulations directed to building owners. Most of these regulations focus on increasing the number of energy efficient buildings, both new and retrofitted, since retrofits play an important role in energy efficiency. Overall, this initiative results from the realization that buildings will have a significant impact in fulfilling the 20/20/20-goals of reducing the greenhouse gas emissions by 20%, increasing energy efficiency by 20%, and increasing the share of renewables to 20%, all by 2020.

The Distributed Energy Resources Customer Adoption Model (DER-CAM) is an optimization tool used to support DER investment decisions, typically by minimizing total annual costs or CO_2 emissions while providing energy services to a given building or microgrid site. This paper shows enhancements made to DER-CAM to consider building retrofit measures along with DER investment options. Specifically, building shell improvement options have been added to DER-CAM as alternative or complementary options to investments in other DER such as PV, solar thermal, combined heat and power, or energy storage. The extension of the mathematical formulation required by the new features introduced in DER-CAM is presented and the resulting model is demonstrated at an Austrian Campus building by comparing DER-CAM results with and without building shell improvement options. Strategic investment results are presented and compared to the observed investment decision at the test site. Results obtained considering building shell improvement options suggest an optimal weighted average U value of about 0.53 $W/(m^2 \cdot K)$ for the test site. This result is approximately 25% higher than what is currently observed in the building, suggesting that the retrofits made in 2002 were not optimal. Furthermore, the results obtained with DER-CAM illustrate the complexity of interactions between DER and passive measure options, showcasing the need for a holistic optimization approach to effectively optimize energy costs and CO_2 emissions. The simultaneous optimization of building shell improvements and DER investments enables building owners to take one step further towards nearly zero energy buildings (nZEB) or nearly zero carbon emission buildings (nZCEB), and therefore support the 20/20/20 goals.

Keywords

building retrofits, building shell improvements, decision making modeling, distributed energy resources, microgrid, mixed integer linear programming, strategic decision, zero net energy buildings

1. Introduction

According to the European Commission, buildings represent about 40% of the total final energy demand in Europe, and 36% of all greenhouse gas (GHG) emissions [1, 2]. In OECD countries an increase of the overall electricity consumption of about 25% until 2040 can be expected [3]. In 2040 the share of electricity demand will increase therefore to about 40% [3]. Furthermore, roughly 30% of the total commercial and residential energy consumption in 2040 will be for natural gas, fuel oil, and coal, showing the need to reduce heating and cooling needs. In 2009, the EU committed itself to a very ambitious reduction of about 80 to 95% of GHG emission by 2050 compared to 1990 [4, 5]. To secure the future energy supply in Europe the EU defined the “20/20/20-goal”: reduce the GHG emissions by 20% (based on 1990 values), increase energy efficiency by 20%, and increase the share of renewables to 20% by 2020 [6]. Part of the increase in energy efficiency needs to come from building retrofits. Retrofits can also contribute to an increase in green energy usage. The usage of distributed energy resources (DER) as e.g. photovoltaic, solar thermal systems, combined heat and power (CHP), or heat pumps increases the system efficiency. Growth in electricity use is also driven by heating, ventilation, and air conditioning (HVAC) systems as well as heat pumps and other electrical loads. Direct reduction of energy demand and increased use of renewable energy sources are the main activities for decreasing Europe’s energy dependency and its GHG emissions. Building retrofit combined with enhanced energy management systems is seen as important concepts to affect the security of energy supply in both the medium and long term. Previous studies have shown the potential benefits of retrofits combined with highly efficient generation technologies at a large scale and often demand reduction measures even proved to generate greater economic benefits than investing in the generation side only [7, 8].

The consideration of all this possible combinations enables the transformation of energy intensive buildings into nearly zero energy buildings (nZEB) respectively zero energy buildings (ZEB) [9].

Models and optimization tools are necessary to enable research as well as building owners to analyze the recent situation regarding DER and possible improvements as e.g. investment in new boiler technologies, in new green energy systems, and in the refurbishment of the existing building shell. Such tools should be able to consider all possible conceivable combinations of possible improvements and should thereby be able to find the real economic and/or environmental optimum.

Most available optimization tools for finding economic and environmental sound building and distributed energy resources (DER) technologies for microgrids or buildings are not able to consider passive improvements within the optimization process in a holistic way. A microgrid (µgrid) is a semiautonomous grouping of generating sources (e.g. PV, solar thermal) and end-use sinks (e.g. electricity demand, heating and cooling demand) that are placed and operated for the benefit of its owner that operate in a coordinated way [10]. Mostly, a certain modeling and implementation strategy is assumed that suggests first passive measures and then renewables or other technologies. However, this assumed path eliminates synergies between passive and DER technologies and risks higher costs due to oversizing for example as demonstrated by the Austrian example in this paper. From a technical point of view most tools either cannot consider passive measures at all or need to interface with external building simulation tools as e.g. EnergyPlus.

In this paper, a new extended version of DER-CAM is presented with the ability to consider passive measure improvement options in the optimization process, in addition to the standard DER investment options such as local renewables or micro combined heat and power (CHP). This means that, in this extended formulation, DER-CAM is now able to decide based on given investment costs and performance parameters if passive improvements (exchange of windows, doors, increased insulation thickness on wall, ground, and ceiling) should be considered within the overall investment decisions, which was not previously possible in DER-CAM and has not been explicitly addressed in the existing DER literature. By simultaneously considering passive measures and standard DER options, the new formulation of DER-CAM has the ability to model and capture synergies between all of these different options, thus providing investment solutions that may have a greater contribution towards energy efficiency in buildings than those obtained by separately evaluating retrofits and traditional DER options.

The mathematical formulation of the new capabilities added in DER-CAM is described and the resulting model is applied to a Campus building in Austria that was refurbished in 2002. Two multi-objective frontiers are presented, where the trade-off between cost and CO_2 minimization objectives for the Austrian example are shown. The first one without passive measures enabled and the second one with passive measures enabled in DER-CAM supporting nearly zero carbon emission buildings (nZCEB). The Campus building is used as an office complex and for education purposes. While DER-CAM considers hourly load profiles and their effects on building shell refurbishment other work as described in [11, 12] is based on yearly consumptions and small sets of technologies (window exchange, additional wall and roof insulation, and solar collectors).

The structure of this paper is as follows:

- Section 2 describes modeling tools which can be used to increase the energy efficiency in buildings respectively microgrids.
- Section 3 describes the basic mathematical model of DER-CAM with special focus on the building shell improvement concept within DER-CAM, which was designed by the authors.
- Section 4 shows the strategic DER-CAM results based on an Austrian Campus building.
- Section 5 summarizes the research contributions and describes further steps for DER-CAM.

2. Modeling tools

As mentioned, a microgrid is a group of interconnected loads and DERs within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. Several available tools can be used for increasing the energy efficiency in buildings respectively microgrids [13].

Publicly available tools are considered within this paper and are briefly discussed below.

The tools can be divided into the following categories [14]:

• accounting and simulation tool	RETscreen, TrnSys, EnergyPlus, EnergyPLAN
• optimization tool	DER-CAM, EnRiMa, HOMER

Out of this list, DER-CAM is the only available optimization tool with the ability to consider DER investment decisions along with retrofit decisions, given that EnRiMa is still under development and has not been released to the general public. The other tools have been created either for financial analysis or for simulation purposes.

2.1 Accounting and Simulation Tools

2.1.1 RETScreen

The “Renewable Energy Project Analysis Software” (RETScreen) was developed from RETScreen International, Canada and is operated by Natural Resources Canada [15].

RETScreen is an Excel-based program to manually analyze clean energy projects based on e.g. calculated payback periods. This is done by defining different system configurations that can include several technologies such as renewables and CHP. All input parameters have to be defined by the user, requiring significant experience and prior knowledge in order to produce relevant results, although more than 1000 different technologies (from manufacturers around the globe) are available from the web-site and accessible for the analysis process via simple steps. Results include economic and environmental performance indicators, allowing a quick assessment of different solutions. RETScreen can consider not only generation technologies, but also passive improvements scenarios defined by the user.

2.1.2 EnergyPLAN

EnergyPLAN has been developed at Aalborg University, Denmark within the Department of Development and Planning since 1999 [16].

EnergyPLAN is a Windows-based deterministic simulation program where a timestamp of one hour is considered through the overall analyzed year. Analytical programming (use of iterations and advanced mathematical tools) results in a fast performing model calculation. No linear optimization for investment and planning takes place. Electrical, cooling, heating, and process heat demand can be considered as well as transport demand.

The user can add passive improvements as fixed costs within the “various additional investment costs”.

2.1.3 EnergyPlus

EnergyPlus has been developed for the US Department of Energy (DOE) Energy Efficiency & Renewable Energy (EERE) group by the Lawrence Berkeley Simulation Research Group, the Building Systems Laboratory at the University of Illinois, the Florida Solar Energy Center, National Renewable Energy Laboratory, and others [17].

EnergyPlus can be used on Windows, Macintosh and Linux. By the use of EnergyPlus the heating, cooling, and electricity load of a given building is simulated by using the detailed thermodynamic equations. The surplus of EnergyPlus is the consideration of the building thermal mass and the interaction of the single building system components in a very detailed way. The output is a detailed load curve for heating, cooling, electricity, and carbon emissions with a desired timestamp ranging from one hour to one minute.

The simulation tool EnergyPlus results in building energy loads which can be used in optimization tools as DER-CAM.

2.1.4 TrnSys

The "Transient Systems Simulation Program" (TrnSys) has been developed since the 1975 with the University of Wisconsin. Its modular program design is able to solve complex energy system problems by the use of smaller predefined components (so called 'types') [18].

TrnSys is a simulation program. It can be used to simulate yearly thermal heating and cooling results of e.g. a building on an hourly base. The result of TrnSys can be monthly and yearly summaries of the energy usage.

The simulation tool TrnSys results in building energy loads which can be used in optimization tools.

2.2 Optimization Tools

2.2.1 Homer

The National Renewable Energy Laboratory (NREL), US started in 1993 the development of the "Hybrid Optimization Model for Electric Renewables" (Homer) which is now available from HOMER Energy LLC [19].

Homer is a Windows-based program. It is able to deal with electrical and thermal load curves on a resolution up to 1 minute. The main advantage of Homer is the ability to do sensitivity analyses with little extra effort. The output is a financial analysis covering the energy production, fuel consumption, and emissions. Homer is not able to consider cooling loads. While it optimizes dispatches, it does not optimize investment decisions, despite its classification as an optimization tool. The user has to pre-define the possible technologies and their sizes/capacities and then Homer sorts these combinations according to their results. Therefore, only user predefined combinations of technologies can be considered in the financial analysis.

2.2.2 EnRiMa

Energy Efficiency and Risk Management in Public Buildings (EnRiMa) is a new optimization tool, which is currently under development and financed by the European Union. The overall goal of EnRiMa is to create a multi-objective Decisions Support System (DSS) to improve the energy efficiency by lowering costs and given comfort and financial risks. Therefore, sometimes contradictory goals as minimize cost, cover the energy requirements, minimize emissions, or reduce financial risks are considered. It consists of two modules: an operative and a strategic module. Based on a comfort temperature range and the weather forecast the operative module calculates the energy demand (electricity, heating and cooling) for the day-ahead operation. The strategic module is responsible for the strategic decision making by considering the long-term perspective with multi-stage stochastic scenario trees. The interaction between the operational and the strategic module can be found in Figure 1 [20 - 22]. Considering stochastic parameters as e. g. fluctuating energy prices and unstable building occupancies by the students, the strategic module is generating a set of investment possibilities for the building management. The operative DSS performs the operational optimization for the next day(s). The strategic DSS will determine feasible investment decisions for a given building for the next years. Within the operative DSS the user comfort is the main criterion, which has to be guaranteed. By comparison the strategic DSS is a pure cost and/or emission minimization algorithm for the next years [20 - 22]. However, within EnRiMa's strategic module it is planned to include the passive improvements as a pre-calculated table where the costs and the effects on the heating and cooling load are considered by user input. Thereby, only a user-defined set of technologies and its savings will be considered before the DER optimization takes places. This approach has been chosen to save optimization time due to the stochastic nature of the strategic EnRiMa module, but might limit the optimization capabilities.

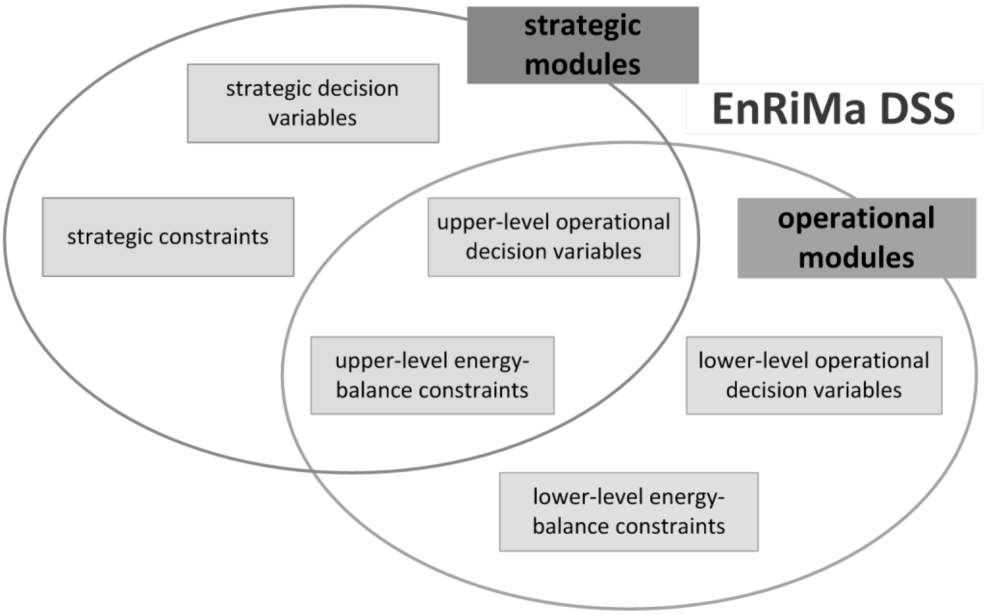

Figure 1: Modular approach of EnRiMa DSS [21]

2.2.3 DER-CAM

The "Distributed Energy Resources Customer Adoption Model" (DER-CAM) has been developed by the Lawrence Berkeley National Laboratory (LBNL), US since 2000 [23 - 26].

The DER-CAM optimization tool is a mixed-integer linear program (MILP) written and executed in the General Algebraic Modeling System (GAMS) [27]. Its objective is typically to minimize the total equivalent annual costs or CO_2 emissions for providing energy services to a given site, including utility electricity and natural gas purchases, plus amortized capital and maintenance costs for any DG investments. The approach is fully technology-neutral and can include energy purchases, on-site conversion, both electrical and thermal on-site renewable harvesting, and partly end-use efficiency investments. Its optimization techniques find both the combination of equipment and its operation over a typical year (average over many historical years) that minimizes the site's total energy bill or CO_2 emissions, typically for electricity plus natural gas purchases, as well as amortized equipment purchases. It outputs the optimal DER and storage *adoption* combination *and* an hourly *operating schedule*, as well as the resulting costs, fuel consumption, and CO_2 emissions. Given its optimization nature and technology-neutral approach, DER-CAM can capture both direct and indirect benefits of having different technologies together, for instance by reflecting the impact of CCHP in cooling loads originally met by electric chillers, thus considering the simultaneity of results.

DER-CAM is basically available in two major versions:

- Investment and Planning DER-CAM and
- Operations DER-CAM

Investment and Planning picks optimal microgrid equipment combinations, based on 36 – one representative week, weekend, and peak day per month, or 84 – seven representative days of hourly energy loads per month to characterize a typical year, as well as technology costs and performance coefficients, fuel prices, and utility tariffs for all possible electricity, heating, cooling, refrigeration, and domestic hot-water demand loads.

The investment and planning version is used to assess the impact of passive measures on future strategic investment decisions. The output is a detailed portfolio on DER technologies and passive measures that should be considered for investments and which are subject to multiple types of different loads which typically are: electricity, cooling, refrigeration, space-heating, water-heating, and natural gas. Besides that a detailed operational planning curve for the desired technologies are provided. On the other hand Operations DER-CAM is used for the optimization of the detailed dispatch in a microgrid for a given period, typically a week ahead, with a time resolution of 5 min, 15 min, or 1 h, assuming the installed capacity is known, and using weather forecasts from the web to forecast requirements [25, 26].

DER-CAM is the only DER optimization tool that offers a free academic web-based version with limited features [28].

This paper focuses on the possibility of building shell improvements: exchange of windows and doors as well as addition of multiple layers of insulation to walls, floors and roofs. The impact of a building refurbishment is part of the objective function by considering the annual costs for the improvement and reduced heating or cooling loads directly in the model. Therefore, DER-CAM considers passive improvements in parallel with the optimal supply technology (as PV, solar thermal, storage, fuel cells, etc.) decisions and hereby finds the optimal investment decision. This first passive measure version of DER-CAM does not consider uncertainty (e.g. in renewable energy output), but a huge effort is underway to transform the deterministic DER-CAM into a stochastic based optimization tool and currently electric vehicles and reliability issues can be considered in the stochastic version of DER-CAM [29].

3. The specific case of passive measures in DER-CAM

The following section presents the relevant DER-CAM formulation to reflect the changes introduced in this work to accommodate possible investments in passive measures. For further information please refer to [30, 31].

Indices

b	building shell components, $b \in \mathbf{B} = \{\text{wall}, \text{window}, \text{door}, \text{ground}, \text{roof}\}$
c	continuous generation technologies, $c \in \mathbf{C} = \{\text{PV}, \text{ST}, \text{AC}\}$, where PV represents photovoltaic panels, ST solar thermal panels, and AC absorption chillers
d	day-types, $d \in \mathbf{D} = \{\text{week}, \text{peak}, \text{weekend}\}$
g	discrete generation technologies, including internal combustion engines (ICE), micro turbines (MT), fuel cells (FC), and gas turbines (GT), with and without heat exchangers (HX), $g \in \mathbf{G} = \{\text{ICE}, \text{ICEHX}, \text{MT}, \text{MTHX}, \text{FC}, \text{FCHX}, \text{GT}, \text{GTHX}\}$
h	hours in a day $h \in \mathbf{H} = \{1,2,\dots,24\}$
i	DER technologies, $i \in \mathbf{I} = \mathbf{J} \cup \mathbf{S}$
j	generation technologies, $j \in \mathbf{J} = \mathbf{G} \cup \mathbf{C}$
k	passive investment options, $k \in \mathbf{K} = \{1,2,\dots\}$, defined for each building shell component b.
m	months in a year, $m \in \mathbf{M} = \{1,2,\dots,12\}$
$n(h)$	hours prior to current hour, $n(h) \in \mathbf{N} = \{1,2,\dots,h-1\}$
p	demand charge control periods, $p \in \mathbf{P} = \{\text{coincident}, \text{on}-\text{peak}, \text{mid}-\text{peak}, \text{off}-\text{peak}\}$, where charges are applied to peak power demand measured over that period; demand charges are a powerful driver for DER adoption
q	opaque building shell components, $q \in \mathbf{Q} = \{\text{wall}, \text{ground}, \text{roof}\}$
s	energy storage technologies, including stationary storage (SS), electric-vehicle storage (EV) and heat storage (HS), $s \in \mathbf{S} = \{\text{SS}, \text{EV}, \text{HS}\}$
u	energy end-uses, including electricity-only (eo), cooling (cl), refrigeration (rf), space heating (sh), water heating (wh), and natural gas loads (ng), $u \in \mathbf{U} = \{\text{eo}, \text{cl}, \text{rf}, \text{sh}, \text{wh}\}$

Parameters

A_b	area of building component b, m^2
$ANN_{i\cup(b,k)}$	annuity rate of investing in DER technology i, or in building shell component b, option k
$C_{u,m,d,h}$	volumetric electricity charges including CO_2 taxes if used, €/kWh
$D_{u,p}$	charges applied to peak power demand for end-use u during period p, €/kW
$DRC_{u,m,d,h}$	volumetric demand response costs, €/kWh
$dx_{q,k}$	thickness of opaque building shell component q, investment option k, m
Fx_b	temperature correction coefficient for building shell component b (see Table 1)
$GENC_{j,u,m,d,h}$	unit cost of energy provided by technology j for end-use u in month m, day type d and hour h, including fuel costs, maintenance costs and CO_2 taxes, €/kWh
$IFix_i$	fixed investment cost of DER technology i, €

$\mathrm{INST}_{b,k}$	installation cost of investing in building shell component b, option k, €
$\mathrm{IVar}_{c\cup s}$	variable investment cost of continuous energy conversion technology c, or storage technology s, €/kW or €/kWh
$\mathrm{LOAD}_{u,m,d,h}$	client energy demand for end-use u, in month m, day-type d, and hour h, kWh
$\mathrm{LOAD}'_{u,m,d,h}$	client energy demand after passive measure investment for end-use u, in month m, day-type d, and hour h, kWh
$\mathrm{MAT}_{b,k}$	cost of materials for investing in building shell component b, option k, €
MaxP_{g}	maximum power output from discrete generation technology g, kW
MFix_{m}	fixed monthly utility charges, €
Rx_{q}	heat transfer coefficient of the existing opaque building shell element q, m^2·K/W
$\mathrm{S}_{m,d,h}$	electricity selling price in month m, day-type d, and hour h, €/kWh
$\mathrm{T}^{int}_{m,d,h}$	interior building temperature in month m, day-type d, and hour h, ºC
$\mathrm{T}^{out}_{m,d,h}$	outdoor environment temperature in month m, day-type d, and hour h, ºC
U_{b}	heat transfer coefficient of existing building shell component b, W/(m^2·K)
$\mathrm{U}'_{b,k}$	heat transfer coefficient of building shell improvement component b, option k, , W/(m^2·K)
$\mathrm{U}'_{q,k}$	heat transfer coefficient of opaque building shell component q, option k, , W/(m^2·K)
$\Delta\mathrm{T}_{u,m,d,h}$	temperature differential considered for recalculating client load of end-use u, in month m, day-type d, and hour h, ºC
$\lambda_{q,k}$	heat conductivity of opaque building shell component q, investment option k, W/(m·K)
φ_{s}	hourly self-discharging in energy storage technology s
η_{i}	energy conversion efficiency for i

Decision Variables

$cap_{c\cup s}$	installed capacity of continuous generation technology c, or storage technology s, kW or kWh
$dr_{u,m,d,h}$	energy demand of end-use u removed by demand response measures in month m, day d, and hour h, kWh
$gen_{j,u,m,d,h}$	useful energy provided by generation technology j for end-use u in month m, day-type d, and hour h, kWh
$inv_{b,k}$	binary decision of investing in building shell component b, option k
num_{g}	number of installed units of discrete generation technology g
$pur_{c\cup s}$	decision to purchase continuous generation technology c, or storage technology s
$sell_{j,u,m,d,h}$	energy sales from generation technology j for end-use u that is exported in month m, day-type d, and hour h, kWh
$sin_{s,u,m,d,h}$	energy input to storage technology s for end-use u, in month m, day-type d, and hour h. kWh
$sout_{s,u,m,d,h}$	energy output from storage technology s for end-use u, in month m, day-type d, and hour h, kWh
$u_{u,m,d,h}$	utility purchase for end-use u, during month m, day-type d, and hour h, kWh
$u_{u,p}$	utility purchase in demand charge control period, kW

While multiple objective functions are generally used in DER-CAM, only the economic objective function is described in equation (1). It considers all energy related costs, including fixed and variable utility costs, and all costs resulting from investing in DER, which includes capital costs, maintenance costs, and operation costs. Finally, energy management measures such as demand response are also included, as well as electricity sales. Changes in the economic objective function introduced in this paper reflect the costs of investing in passive measures, which include material and installation costs, corrected by an annuity rate factor to assess the different lifetime periods of options.

$$\begin{aligned}\min C = &\sum_{\mathrm{m}} \mathrm{MFix_m} + \sum_{\mathrm{m,d,h}} u_{\mathrm{u,m,d,h}} \cdot \mathrm{C_{u,m,d,h}} + \sum_{\mathrm{u,p}} \max u_{\mathrm{u,p}} \cdot \mathrm{D_{u,p}} \\ &+ \sum_{\mathrm{g}} num_{\mathrm{g}} \cdot \mathrm{IFix_g} \cdot \mathrm{ANN_g} + \sum_{\mathrm{cUs}} (pur_{\mathrm{cUs}} \cdot \mathrm{IFix_{cUs}} + cap_{\mathrm{cUs}} \cdot \mathrm{IVar_{cUs}}) \cdot \mathrm{ANN_{cUs}} \\ &+ \sum_{\mathrm{i,u,m,d,h}} \frac{gen_{\mathrm{i,u,m,d,h}}}{\eta_{\mathrm{i}}} \cdot \mathrm{GENC_{i,u,m,d,h}} + \sum_{\mathrm{u,m,d,h}} dr_{\mathrm{u,m,d,h}} \cdot \mathrm{DRC_{u,m,d,h}} \\ &- \sum_{\mathrm{j,u,m,d,h}} sell_{\mathrm{j,u,m,d,h}} \cdot \mathrm{S_{m,d,h}} + \sum_{\mathrm{b,k}} \left(inv_{\mathrm{b,k}} \cdot \mathrm{A_b} \cdot \left(\mathrm{MAT_{b,k}} + \mathrm{INST_{b,k}}\right) \cdot \mathrm{ANN_{b,k}}\right)\end{aligned} \tag{1}$$

As described by this equation, DER technologies are modeled in DER-CAM as either continuous or discrete. This distinction is made as the use of continuous technologies dramatically improves the model run time, and for that reason DER technologies are modeled as continuous whenever their governing economics allow considering a continuous linear cost function and the technology is available in small enough modules so that the capacity can be approximated as a continuous variable (e. g. photovoltaic panels).

The new passive measure capabilities allow investments in five different building shell components (wall, window, door, ground, and roof), each treated individually by DER-CAM. However, it is assumed that investing in the “wall” or “door” component affects all walls or doors in the building. Furthermore, it is assumed that investments in transparent components (windows and doors) mean replacing all occurrences of that component within the building, and investments in opaque components (walls, ground, and roof) represent an additional layer of material that increases thermal performance. It should also be noted that, while we are referring to passive measure investments as applying to all elements of a given building component, it would also be possible to model smaller interventions, such as replacing a few windows or performing a retrofit only in some of the walls. However, and since a since a global U-value is currently considered per building component, these smaller scale interventions would still be reflected in our calculations as a global effect on loads, as improvements options are used to re-calculate the overall thermal loads (heating and cooling) of the building.

The key constraints applied in the model are energy balance constraints and operational constraints that define each technology individually. The energy balance equation is defined by equation (2).

$$\mathrm{LOAD}'_{\mathrm{u,m,d,h}} - dr_{\mathrm{u,m,d,h}} + \sum_{\mathrm{s}} sin_{\mathrm{s,u,m,d,h}} = u_{\mathrm{u,m,d,h}} + \sum_{\mathrm{j}} gen_{\mathrm{j,um,d,h}} + \sum_{\mathrm{s}} sout_{\mathrm{s,u,m,d,h}} - \sum_{\mathrm{j}} sell_{\mathrm{j,u,m,d,h}} \tag{2}$$

This balance equation enforces that in each time step all client energy loads must be met with the exception of energy loads removed due to demand response measures, and these loads must be met either by utility purchase, by local energy conversion or by energy provided by storage technologies. It includes possible sales to the utility, which are forced to zero for all non-electric end-uses by the use of additional constraints. In addition, this balance also accounts for energy exports and inputs to storage devices which add to energy demand in the system, and already reflects changes to original loads introduced by passive investment options explained in Equation (3). It should be noted that only heat transfer by conduction is considered in this equation, and while this is a limitation of the model that will be addressed in future work, the results obtained by this method have been validated by comparing loads obtained by this process with on-site measurements [32].

$$\mathrm{LOAD}'_{\mathrm{u,m,d,h}} = \mathrm{LOAD}_{\mathrm{u,m,d,h}} - \sum_{\mathrm{b,k}} \left(inv_{\mathrm{b,k}} \cdot \left(\mathrm{U}'_{\mathrm{b,k}} - \mathrm{U_b} \right) \cdot \mathrm{A_b} \cdot \mathrm{Fx_b} \right) \cdot \Delta\mathrm{T}_{\mathrm{u,m,d,h}} : \mathrm{u} = \{\mathrm{cl}, \mathrm{sh}\} \tag{3}$$

For subset q with $\mathrm{U}'_{\mathrm{q,k}}$=$\mathrm{U}'_{\mathrm{b,k}}$:

$$\mathrm{U}'_{\mathrm{q,k}} = \frac{1}{\mathrm{Rx_q} + \dfrac{\mathrm{dx_{q,k}}}{\lambda_{\mathrm{q,k}}}} = \frac{1}{\dfrac{1}{\mathrm{U_q}} + \dfrac{\mathrm{dx_{q,k}}}{\lambda_{\mathrm{q,k}}}} \tag{4}$$

$\mathrm{U}'_{\mathrm{b,k}}$ for windows is specified by the user (see Table 4).

$$\Delta\mathrm{T}_{\mathrm{u,m,d,h}} = \begin{cases} 0, & \mathrm{T}^{\mathrm{int}}_{\mathrm{m,d,h}} - \mathrm{T}^{\mathrm{out}}_{\mathrm{m,d,h}} \leq 0 \;\wedge \mathrm{u} = \mathrm{sh} \\ \mathrm{T}^{\mathrm{int}}_{\mathrm{m,d,h}} - \mathrm{T}^{\mathrm{out}}_{\mathrm{m,d,h}}, & \mathrm{T}^{\mathrm{int}}_{\mathrm{m,d,h}} - \mathrm{T}^{\mathrm{out}}_{\mathrm{m,d,h}} > 0 \;\wedge \mathrm{u} = \mathrm{sh} \\ 0, & \mathrm{T}^{\mathrm{int}}_{\mathrm{m,d,h}} - \mathrm{T}^{\mathrm{out}}_{\mathrm{m,d,h}} \geq 0 \;\wedge \mathrm{u} = \mathrm{cl} \\ \mathrm{T}^{\mathrm{int}}_{\mathrm{m,d,h}} - \mathrm{T}^{\mathrm{out}}_{\mathrm{m,d,h}}, & \mathrm{T}^{\mathrm{int}}_{\mathrm{m,d,h}} - \mathrm{T}^{\mathrm{out}}_{\mathrm{m,d,h}} < 0 \;\wedge \mathrm{u} = \mathrm{cl} \end{cases} \tag{5}$$

$$\sum_{\mathrm{k}} inv_{\mathrm{b,k}} \leq 1 \tag{6}$$

$$\mathrm{U}'_{\mathrm{b,k}} < \mathrm{U}_{\mathrm{b}} \tag{7}$$

Heat transfer coefficients in transparent shell component investment options are provided to the model as user input, while heat transfer coefficient in opaque components are recalculated in equation (4) depending on the possible investment options. Equation (5) is necessary to calculate the temperature difference (ΔT) for the given internal and ambient air temperatures which reflects the change in heating and cooling load for the given building. As each building shell type can only be subject to one improvement equation (6) needs to be introduced. Only building shell improvements, which are indicated by a decrease in the U value of a building shell part, are considered by the optimization process, and therefore, equation (7) is necessary to ensure this.

Other specific balance equations also exist for technologies such as storage devices, as shown in equation (8):

$$\sum_{\mathrm{n=1}}^{\mathrm{h}} \sum_{\mathrm{u}} \left(sin_{\mathrm{s,u,m,d,n}} - sout_{\mathrm{s,u,m,d,n}} \right) \cdot (1 - \varphi_{\mathrm{s}})^{\mathrm{h-n}} \leq cap_{\mathrm{s}} \tag{8}$$

In this example it is stated that in any time step h the cumulative net input in the storage device s, $\left(sin_{\mathrm{s,u,m,d,n}} - sout_{\mathrm{s,u,m,d,n}} \right)$, including losses over time due to self-discharge, determined by coefficient φ_{s}, can never exceed the installed capacity cap_{s}.

Examples of operational constraints can include technical restrictions in terms of energy output, or constraints that ensure that different energy end-use types are limited to the appropriate technologies and variables which are shown in equation (9) and (10).

$$gen_{\mathrm{g,m,d,h}} + sell_{\mathrm{g,u,m,d,h}} \leq num_{\mathrm{g}} \cdot \mathrm{MaxP_g} \tag{9}$$

$$sell_{\mathrm{i,u,m,d,h}} = 0 \; \forall \, \mathrm{u} \neq \mathrm{eo} \tag{10}$$

In DER-CAM passive technologies are chosen such that results reflect the benefit of heating demand displacement which lowers building loads, and therefore, the on-site generation requirement. Site-specific inputs to the model are pre-optimization end-use energy loads, detailed electricity and natural gas tariffs, and DG investment options [31].

Figure 2 shows a high-level schematic of all building energy flows modeled in DER-CAM. For this we use Sankey diagrams, which show in a graphical way how loads can be met by different resources at given efficiencies. Thus, a Sankey diagram provides a full view of possible resources that can be considered within the optimization. Available energy inputs to the site are solar radiation, utility electricity, utility natural gas, biofuels, and geothermal heat. For a given site, DER-CAM selects the economically and/or environmental optimal combination of utility electricity purchase, on-site generation, storage and cooling equipment required to meet the site's end-use loads at each time step. The first estimate of the loads ($LOAD_{u,m,d,h}$) is in general provided by building simulation tools as e.g. EnergyPlus. However, the described passive measure approach now directly models the loads at the same time when DER technologies are optimized. In other words, DER-CAM looks into the optimal combination and operation of technologies to supply the services on the right hand side of Figure 2. All the different arrows in Figure 2 represent energy flows and DER-CAM optimizes these energy flows to minimize costs or CO_2 emissions. Black arrows represent natural gas or any bio-fuel, light grey represents electricity, and grey heat and waste heat, which can be stored and/or used to supply the heat loads or cooling loads via absorption cooling.

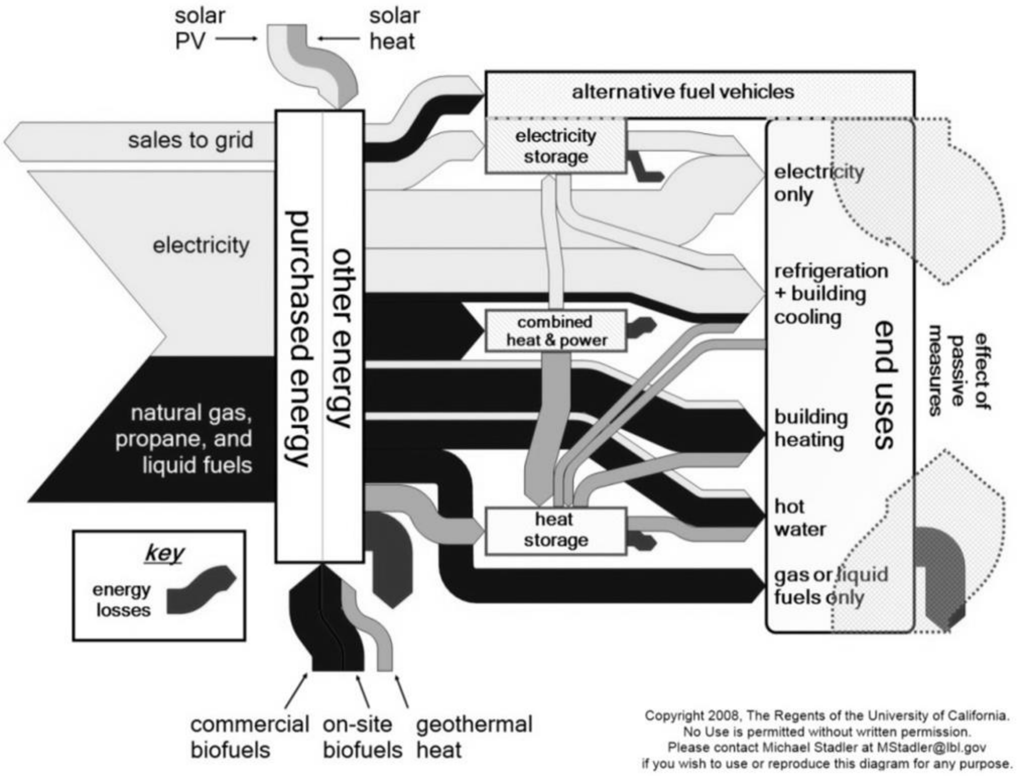

Figure 2: High level schematic of DER-CAM [31]

The improvement of windows or doors is modeled as a replacement within this model (see effect of passive measures on the right hand-side of Figure 2). The improvement of wall, ground, and roof elements is done by adding new layers of insulation.

Considering the temperature correction coefficient $F_{x,i}$ in equation (3) is necessary as there are differences in the thermal behavior or the heat losses and gains depending on the material bordering the building shell (see Table 1). This follows the German Standard DIN 4108-BI2 used in this work to calculate loads.

Table 1: Temperature correction coefficient ([33])

building shell against …	$F_{x,i}$ [-]
air	1.0
soil	0.6

Within DER-CAM we assume that an improvement of the U value will decrease the heating load and increase the cooling load as a static building energy load model is considered within the optimization process as a starting point. However, the findings in [34] suggest that cooling load and U value do not correlate strongly and this needs further cooling research and improvements within DER-CAM.

4. Case Study

The case study considers an Austrian Campus building. About 35 employees and about 600 students are based at that Campus building. The average annual thermal heat required for heating is about 220 MWh_t. The Campus is connected to a local biomass-fired district heating system. The average annual electricity demand is about 200 MWh_e and the Campus is subject to a flat electric rate of 0.15€/kWh tariff. More information on the test site can be found at [32].

The basis for all strategic optimizations is the assumption that the buildings at the Campus building have not been refurbished in 2002. For the DER-CAM test runs we assume that the buildings were not upgraded in 2002 and assume building properties from the construction in the 1970's. This allows us to compare the optimal result with the current implemented technologies. Table 2 defines the initial situation of the building shell. Table 3 and Table 4 show how non-transparent (e.g. wall) improvements and transparent (e.g. window) replacements are specified as input data within DER-CAM. While for non-transparent building shell components the optimization process can add one additional insulation layer, transparent buildings parts are replaced entirely. The insulation thickness for opaque elements is chosen by DER-CAM by the usage of a decision variable.

Table 2: Considered existing building shell quality within DER-CAM ([32] [35] & own calculations)

building shell type	considered U values U_b (basis 1970's) [W/(m²·K)]	real implemented U values in 2002 [W/(m²·K)]	surface [m²]
wall	1.10	0.31	3261
ground	0.90	0.39	2088
roof	0.70	0.34	2088
window	2.30	1.34	390
door	1.70	1.95	136
weighted average	1.01	0.42	n/a

Table 3: Possible wall improvements within DER-CAM ([35] & own calculations)

material	heat conductivity [W/(m·K)]	optimization increments [m]	investment cost [$/m³]	installation cost [$/m²]
insulation	0.038	0.025	45	25

The investment costs reflect material costs while the installation costs reflect the required amount of money to install the material properly.

Table 4: Possible window replacements within DER-CAM ([35] & own calculations)

configuration name	U value $U'_{b,k}$ [W/(m²·K)]	investment cost [\$/m²]	installation cost [\$/m²]
window1	2.60	250	60
window2	1.30	400	65
window3	0.75	750	90

Table 5 defines the investment parameters for continuous DER technologies. This kind of technology can be chosen in any quantity by the optimization. Table 6 and Table 7 define the investment parameters for discrete technologies without and with heat exchange technologies. Table 8 defines the technical parameter for electrical and thermal storage technologies.

Table 5: Continuous investment parameters within DER-CAM ([20])

parameter	fixed cost[1] [\$ per installation]	variable costs [\$/kW or \$/kWh[2]]	lifetime [years]	fixed maintenance [\$/kW or \$/kWh]
electric storage	295	193	5	0.00
heat storage	10,000	100	17	0.00
absorption chiller	93,912	685	20	1.88
photovoltaic	3,851	3,237	20	0.25
solar thermal	0	500	15	0.50

Table 6: Discrete investment parameters, without heat recovery within DER-CAM ([20])

parameter	capacity [kW]	capital costs [\$/kW]	variable maintenance cost [\$/kWh]	lifetime [years]	electric efficiency [%, HHV]
ICE	60	2,721	0.02	20	29
MT	60	2,116	0.02	10	25
FC	60	2,382	0.03	10	36

Table 7: Discrete investment parameters, with heat recovery within DER-CAM ([20])

parameter	capacity [kW]	capital costs [\$/kW]	variable maintenance costs [\$/kWh]	lifetime [years]	electric efficiency [%, HHV]	HPR [-]
ICE-HX	60	3,580	0.02	20	29.0	1.73
MT-HX	60	2,377	0.02	10	25.0	1.80
FC-HX	60	2,770	0.02	10	36.0	1.00

Note: All technologies running on natural gas.

Abbreviations: HX – heat exchanger (using combined heat and power capabilities), HPR – heat-power ratio, ICE – internal combustion engine, GT – gas Turbine, MT – micro-turbine, FC – fuel cell.

Table 8: Energy storage (electrical and thermal) parameters within DER-CAM ([20])

parameter	electrical [-]	thermal [-]	description

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[1] Regardless of the installed capacity.

[2] Storage technology costs are expressed in \$/kWh.

parameter	electrical [-]	thermal [-]	description
charging efficiency	0.90	0.90	portion of energy input to storage that is useful
discharging efficiency	1.00	1.00	portion of energy output from storage that is useful
self-discharging	0.001	0.01	portion of state of charge lost per hour
maximum charge rate	0.10	0.25	maximum portion of rated capacity that can be added to storage in an hour
maximum discharge rate	0.25	0.25	maximum portion of rated capacity that can be withdrawn from storage in an hour
minimum state of charge	0.30	0.00	minimum state of charge as apportion of the rated capacity

For the calculation of the annuity a building shell lifetime of 20 year is considered. For all other investments a maximum payback period of 12 year has been defined. The interest rate has been assumed with 6%.

Since this work is intended to show the trade-off between energy cost and CO_2 emission reduction, DER-CAM allows optimizing the weighted building energy costs and CO_2 emissions at the same time by using a multi-objective approach described by equation (11). By increasing *ω,* more focus on CO_2 emission reduction is placed. The cost reference and the carbon emission reference parameters are derived from the do-nothing case (no investments in DER and passive measures) results.

$$\min\left((1-\omega)\cdot\frac{C}{\text{RefCost}}+\omega\cdot\frac{CO_2}{\text{RefCO}_2}\right) \tag{11}$$

where:

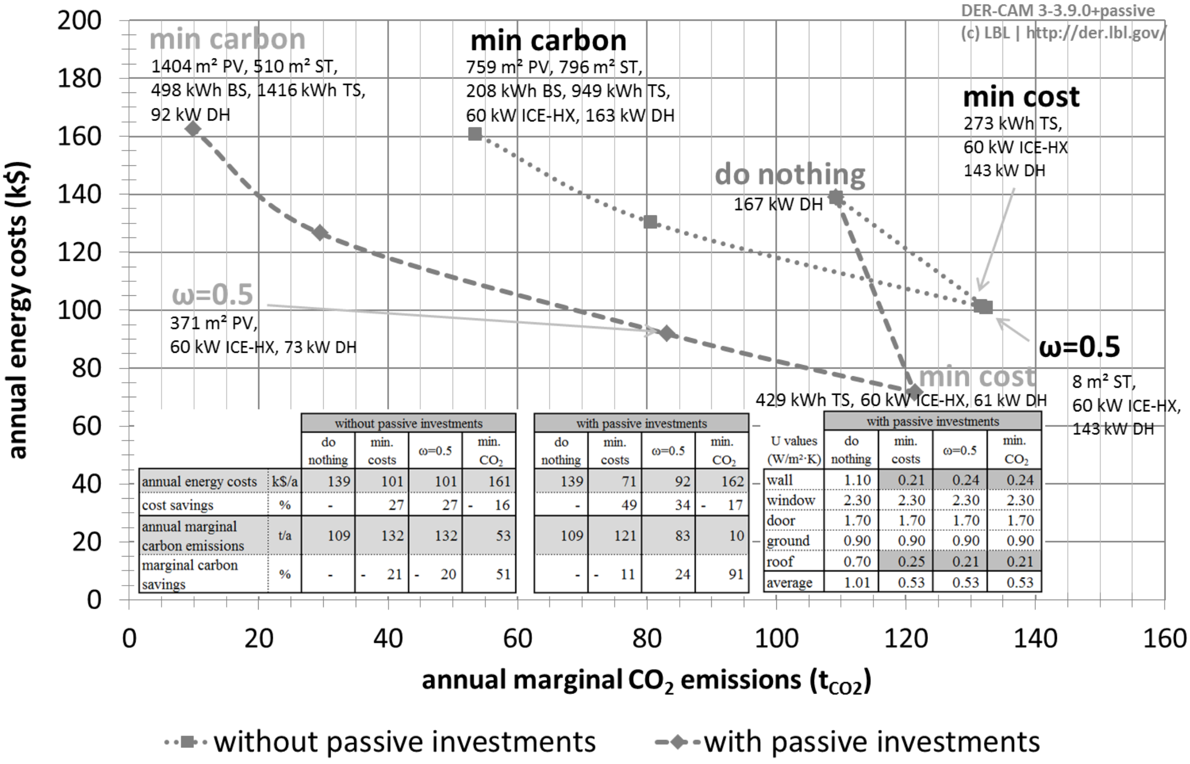
ω	weight factor (0..1) (-)
C	total costs for optimization case ($)
CO_2	total amount of carbon emissions for optimization case (kg)
RefCost	cost reference parameter to make equation unit less ($)
RefCO_2	carbon emission reference parameter to make equation unit less (kg)

In this study, it was assumed that improving the energy efficiency at the Campus would have the potential to displace marginal CO_2 emissions from the local utility, corresponding to an estimated 440gCO_2/kWh [20].

Figure 3 shows the multi-objective DER-CAM results. The dotted line represents the multi-objective results for several optimizations without the passive improvements turned on - only DER is allowed in these optimizations (see Table 5 to Table 8 for input data). The dashed line shows the results with

DER options and passive improvements (U value changes) turned on (see Table 2 to Table 4 for passive input data).

All cases with and without passive improvements, except the pure CO_2 minimization case, are utilizing a 60 kW natural gas fired internal combustion engines (ICEs) system with heat exchanger (HX). Both cost minimization cases are showing a combination of ICE-HX, district heating (DH), and thermal storage (TS) as optimal solution. The ω=0.5 optimization case with passive improvements selects PV while the optimization case without passive improvements selects solar thermal (ST) as optimal renewable technology (see Figure 3).



		without passive investments				with passive investments			
		do nothing	min. costs	ω=0.5	min. CO_2	do nothing	min. costs	ω=0.5	min. CO_2
annual energy costs	k$/a	139	101	101	161	139	71	92	162
cost savings	%	-	27	27	- 16	-	49	34	- 17
annual marginal carbon emissions	t/a	109	132	132	53	109	121	83	10
marginal carbon savings	%	-	- 21	- 20	51	-	- 11	24	91

	with passive investments			
U values (W/m²·K)	do nothing	min. costs	ω=0.5	min. CO_2
wall	1.10	0.21	0.24	0.24
window	2.30	2.30	2.30	2.30
door	1.70	1.70	1.70	1.70
ground	0.90	0.90	0.90	0.90
roof	0.70	0.25	0.21	0.21
average	1.01	0.53	0.53	0.53

Figure 3: Comparison of strategic optimization runs for the Austrian Campus building
Abbreviations: PV: photovoltaic; ST: solar thermal; BS: battery storage; TS: thermal storage; ICE-HX: internal combustion engine (ICE) with heat exchanger (HX); DH: biomass fired district heating; Note: ω=0.5 means that the optimization focuses equally on cost and CO_2 minimization.

An interesting result is that all passive improvement optimization cases along the dashed line invest in the building shell to decrease the average U value to about 0.53 W/(m²·K) (see Figure 3 and the table on the right hand-side). The cost minimization case without passive improvements results in annual building energy costs (including amortized capital costs) of 101 k$ and CO_2 emissions of 132 t/a. In contrast, the cost minimization case with passive improvements results in annual building energy costs (including amortized capital costs) of 71 k$ and CO_2 emissions of 121 t/a. With a gross heated floor space area of 4100 m^2 [32] the average costs per m^2 floor space area result to 17$ for the “min cost” case and to 40$ for the “min carbon” case considering passive measures. This means that passive measures are attractive for building owners to reduce their energy costs. The optimization case “minimize CO_2” (ω=1) is limited to maximum costs of 150% of the base case do-nothing case to limit the financial impact on the building owner. However, as can be seen from Figure 3, this hard constraint is not binding and the 50% cost increase is not reached. The do-nothing case reflects costs and emissions where all energy needs to be purchased from the utility. In our case this also means that biomass fired district heating is considered in the do-nothing case. In both scenarios with and without passive measures the costs for the “minimize CO_2” case is about 16% respectively 17% above the do-nothing case.

For the given energy prices and building improvement costs the best average U value within the optimization results is about 0.53 $W/(m^2 \cdot K)$. Today’s real average U value of around 0.42 $W/(m^2 \cdot K)$ is about 20% lower as DER-CAM’s optimal solution. The optimal solution also considers the interaction with distributed energy resources as PV or solar thermal. As a consequence the Austrian Campus is well-placed even for times when the energy costs will further increase and the Austrian Campus building can almost reach zero CO_2 emissions as shown by Figure 3 and the dashed line.

The minimize cost case with passive improvements is mainly based on a 60 kW_t natural gas fired CHP system, a heat storage and the district heating to fulfill the overall heating demand. On the other hand the minimize carbon case with passive improvements is mainly based on heat from the district heating system and heat from a solar thermal system.

The observed annual energy costs and CO_2 emissions for Campus Pinkafeld, after the retrofit in 2002, are about 73k$ respectively 103t. The DER-CAM minimize cost run with passive improvements shows optimal costs at about 71k$ which is about 3% lower as today’s energy bill. As this case minimizes the costs the annual marginal emissions are about 121t which is an increase of about 17%.

Table 9 and Figure 4 show the duration of the optimization runs on a Windows 2008R2 Server with 16 CPUs and 72 GB of RAM where the solver is allowed to use four threads (cores) at the same time. Stop criteria for the optimization process is an optimality gap of less than 3% or an optimization run time of one hour. The average computation time increases from 341 s without the consideration of passive measures to about 728 s by considering them. However, this increase is mostly driven by one run, the min cost run (see Figure 4). It seems like that passive measures and DER technologies are in strong economic competition and this increases the run time extremely in this case. As soon as carbon minimization is chosen, the dominance of DER technologies seems to be broken and the choice is made very fast. All optimization runs involving passive measures and CO_2 minimization (ω>0) show reduced or very similar optimization times compared to the cases without passive measures.

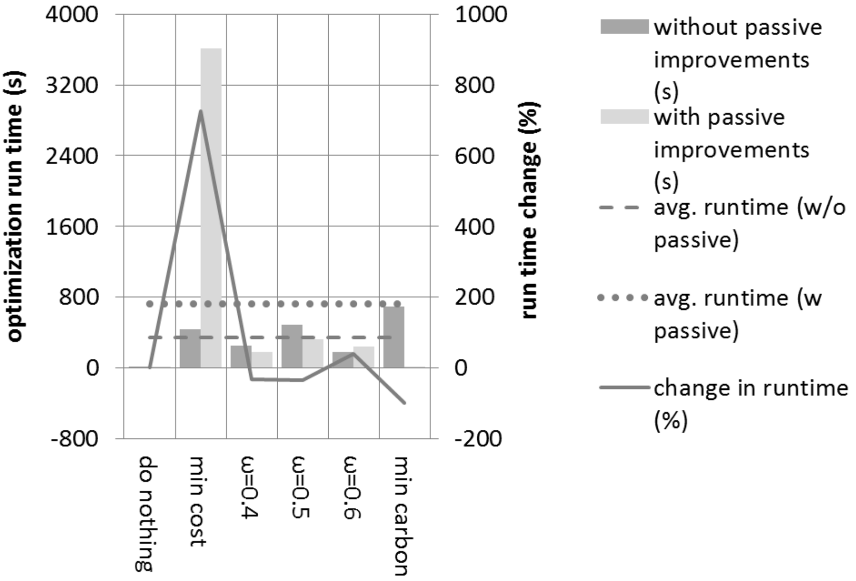


Figure 4: Optimization performance DER-CAM runs (DER-CAM)

Table 9: Duration of the DER-CAM optimization runs (DER-CAM)

optimization run	without passive improvements [s]	with passive improvements [s]	change in runtime [%]
do nothing	1.1	1.1	n/a
min cost	437.3	3616.2	726.9
ω=0.4	254.4	174.6	-31.4
ω=0.5	483.7	319.5	-33.9
ω=0.6	174.1	244.6	40.5
min carbon	696.2	14.0	-98.0
average run time	341.1	728.3	120.8

Abbreviations: s: seconds; n/a: not available.

The “average runtime (w passive)” is the average of all done optimizations with passive improvements while the “average runtime (w/o passive)” is the average of all optimizations without passive improvements (see Figure 4).

5. Conclusions

Within the European Union (EU) the total demand of final energy for buildings (e.g. houses, offices, and shops) is about 40%. Buildings are responsible for about 36% of greenhouse gas emissions in the EU. To secure the future energy supply in Europe the EU defined the “20/20/20-goal”: reduce the GHG emissions by 20% (based on 1990 values), increase energy efficiency by 20%, and increase share of green energy to 20%. Building retrofit combined with enhanced energy management systems is seen as important concepts to affect the security of energy supply in both medium and long term. The consideration of all this possible combinations enables the transformation of energy intensive buildings into nearly zero energy buildings respectively zero carbon emission buildings.

DER-CAM was chosen to consider strategic decision making with the possibility of considering passive improvements, DER technologies, and comparing the results with the existing building shell properties as it is the only tool to the knowledge of the authors with this capability. Compared to the observed annual energy costs, at an Austrian Campus building, the DER-CAM cost minimization result is about 3% lower while the marginal carbon emissions are about 17% higher as the minimize cost run which considers passive improvements. However, the DER-CAM CO_2 minimization case shows nearly zero carbon emission building conditions and a cost increase of 16% compared to the no-invest case.

For the given energy prices and building improvement costs the best average U value within the optimization results is about 0.53 W/(m²·K). Today’s real average U value of around 0.42 W/(m²·K) is about 20% lower as DER-CAM’s optimal solution, which also considers the interaction with distributed energy resources as PV or solar thermal. Therefore, the Austrian Campus building is well-placed even for times when the energy costs will increase and can almost reach zero CO_2 emissions quite easily. However, the results also show how complex the technology interactions can be and that the optimal adopted DER technology capacities can change depending on the objective function and this makes the case for a holistic optimization approach as demonstrated by DER-CAM in this paper.

Other DER-CAM work currently adds stochastic attributes to DER-CAM and the next step of our research is to enhance DER-CAM in such a way that technology reliability can be modeled in more detail. Also, a next step within the implementation of the passive improvements in DER-CAM is to consider different g values for window and door exchanges as this influences the solar gains. Finally, a more sophisticated modeling of cooling loads, beyond U-value influence, is needed to capture internal heat loads, etc.

Acknowledgment

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