Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

REEL Demo – Romande Energie ELectric network in local balance Demonstrator

Deliverable: 5a best investment strategies when prosumer capacities are increased in the grid

Demo site: Rolle

Developed by
Luc GIRARDIN (EPFL-IPESE)
Luise MIDDELHAUVE (EPFL-IPESE)
Ermanno LO CASCIO (EPFL-IPESE)
François MARECHAL (EPFL-IPESE)

[Sion, 27.02.2021]

Contents

Nomenclature

ACRONYMS

AR	Annual Revenues
BA	Battery
BES	Building Energy System
BO	Boiler
CAPEX	Capital Expenses
CHP	Combined Heat and Power
COP	Coefficient Of Performance
DHC	District Heating and Cooling
DHW	Domestic Hot Water
EH	Electrical Heater
ERA	Energy Reference Area
GIS	Geographic Information Systems
GU	Grid Usage
GWP	Global Warming Potential
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
IRR	Internal Rate of Return
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCoE	Levelized Cost of Electricity
MER	Minimum energy requirements
MILP	Mixed-Integer Linear Programming
MOO	Multi-Objective Optimization
NPV	Net Present Value
OCC	Occupancy
OPEX	Operational Expenses
PCA	Principal component analysis
PV	Photovoltaic
PVC	PV curtailment
PVP	Photovoltaic Penetration
RES	Renewable Energy Share
SC	Self-Consumption
SH	Space Heating
SOFC	Solid Oxide Fuel Cell
SS	Self-Sufficiency
STO	Storage
TOTEX	Total Expenses
UES	Urban Energy System
V2G	vehicles-to-Grid

Executive summary

Political authorities, energy operators and other stakeholders have the responsibility to implement energy transition pathways by increasing decentralised renewable energy generation. As the main stakeholder, authorities often lack the appropriate tools to frame and encourage the transition and to monitor the impact of energy transition policies. On the other hand, network operators need appropriate frameworks and guidelines to implement the transition with a sustainable business perspective.

This report capitalize on previous work [1, 2, 3, 4, 5] which uses a data driven approach based on geographical information system (GIS) and machine learning techniques to generate investment pathways towards decentralised energy generation.

This report takes a closer look at the economic, environmental, technical and security impact of the development of decentralized energy systems.

Firstly, Chapter 1 is looking back at the definition of performance indicators, leading to a better understanding of (i) the logic behind the selection of local system boundaries to evaluate energy efficiencies, (ii) the growing importance of grey energy and (iii) the necessary shift to hourly time scale for proper life cycle assessment of the future smart grid, while on the same time, (iii) the need to consider horizon greater than 20 years for investment planning.

Secondly, Chapter 2 shows how long-term investment planning methodology, which is targeting big energy consumers, can favor the emergence of future decentralized energy infrastructure, while harvesting energy from the local environment.

Chapter 3 demonstrates, by optimising solar panel layout in the RE-Demo test case, that grid-aware district scale approaches are required to identify the best investment strategies.

Finally, Chapter 4 presents upcoming opportunities for investments in the digitalization of future smart grids.

1. Description of deliverable and goal

The present deliverable aims to provide tools and guidelines for decision makers to identify the best investment strategies when prosumer capacities and renewable energy are increased in the grid. It leverages case studies and recent publications. The chapters of this report are raising the following strategic aspects:

- the selection and use of key performance indicators to evaluate the trade-off between centralized and decentralized investment strategies;
- the development and use of a long-term investment methodology for the development of local energy infrastructure in the vicinity of big energy consumers;

- the elaboration of optimal investment strategies in decentralised grid-aware layout of photovoltaic panels;
- the future market of smart grid digitalization .

1.1. Research questions

Chapter 1: Key performance indicators for decentralized investments strategies In practice, some observations are questioning the development of decentralized urban energy systems, such as apparent low exergy efficiency, unclear definition of the boundaries in a context of certified renewable energy promotion, the lack of references and uniformity in the computation of Life Cycle Assessment (LCA) indicators and sometimes, the presentation of results penalizing district heating and cooling network and solar energy.

Chapter 2: Long term investment planning methodology Industrial process integration based on mixed integer linear programming (MILP) has been used for decades to design and improve industrial processes. The technique has later been extended to solve multi-period and multi-scale problems for the design of urban energy systems.

The literature review carried out in the field of long-term energy planning tools has revealed a lack of studies focusing on urban major consumers. Major energy consumers, such as hospital complexes, airports, or educational campuses can act as a driving force for the development of renewable energy cities by attracting profitable large scale energy networks and infrastructure. Methodology and tools is indeed required for the elaboration of coordinated investment scheduling strategies to promote renewable and efficient urban energy infrastructures shaping the future energy context for the next decades.

Chapter 3: Investment in Grid-Aware Layout of photovoltaic panels There exists a gap in the state-of-the-art at the intersection between studies focusing on building energy systems (BES), which only include a very simplified representation of the energy generated by PV panels, and studies focusing on the optimal placement of PV panels, which never include how this affects, and is affected by, the integration with other parts of the BES. This work therefore aims to investigate the following research questions:

- What is an optimal placement of PV panels (orientation and tilt) from the perspective of the individual building and of the grid? How does it depend on problem parameters such as the load profile and the characteristics of the building?
- What are the principles that should be adopted when choosing the placement of increasing quantities of PV panels on the roof of the building?
- What is the magnitude of the error induced by the assumption of only horizontally installed PV panels in energy system planning models?
- How are different policies for subsidizing the installation of PV panels impacting the "optimal" orientation?

Chapter 4: The future digitalization of smart grids Ancient Romans called *urbs* the set of buildings and infrastructures, and *civitas* the Roman citizens. Today instead, while the society is surfing the digital tsunami, *urbs* and *civitas* tend to become much closer, almost merging, that we might attempt to condensate these into a single concept: *smartgrid*. Internet of things, artificial intelligence, blockchain, quantum cryptography is only a few of the technologies that are likely to contribute to determining the final portrait of the future smart grid. However, to understand the effective sustainability of complex grids, specific analytical method and tools are required.

1.2. Novelty of the proposed solutions compared to the state-of-art

Chapter 1: Key Indicators for decentralized investments strategies The study has, for the first time, highlighted the correlation between more than thirty indicators, allowing to better understand the trends in the emergence of decentralized urban energy systems (UES).

Chapter 2: Long-term investment planning methodology The proposed methodology generates optimal alternatives for the replacement of various energy supply units and systems, while considering the evolution of the energy demand and the availability of the energy resources in a long-term perspective. The originality of the developed method lies in the integration of a multi-period MILP formulation to generate long-term investment planning scenarios.

Chapter 3: Investment in Grid-Aware Layout of photovoltaic panels Compared with existing building energy system (BES) optimization approaches reported in literature, the contribution of PV panels is modeled in more detail, including a more accurate solar irradiation model and the shading effect among panels. Compared with existing studies in PV modeling, the interaction between the PV panels and the remaining units of the BES, including the effects of optimal scheduling is considered.

Chapter 4: The future digitalization of smart grids A new taxonomic framework has been developed starting from a general analysis of the emerging solutions, identifying intersectoral synergies and limitations with respect to the 'smart grid' concept.

1.3. Description

The report in divided in chapters leveraging on the following publications:

Chapter 1, p.9	Luise Middelhauve, Alessio Santecchia, Luc Girardin, François Maréchal, and Manuele Margni. Key performance indicators for decision making in building energy systems. Proceedings of ECOS 2020, 2020	[6]
Chapter 2, p.19	Bastien Bornand, Luc Girardin, Francesca Belfiore, Jean-Loup Robineau, Stéphane Bottallo, and François Maréchal. Investment planning methodology for complex urban energy systems applied to a hospital site. Frontiers in Energy Research, 2020	[7]
Chapter 3, p.28	Luise Middelhauve, Francesco Baldi, Stadler Paul, and François Maréchal. Grid-aware layout of photovoltaic panels in sustainable building energy systems. Frontiers in Energy Research, 2021	[8]
Chapter 4, p.38	Ermanno Lo Cascio, Luc Girardin, Zhenjun Ma, and François Maréchal. How smart is the grid? Frontiers in Energy Research, 2021	[9]

2. Achievement of Deliverable

The results of this work have been published in open-access journals and have been presented to the industrial partners in order to support the elaboration of management and planning strategies for the energy transition in the RE-Demo zone.

2.1. Date

This deliverable is handed in February 2021.

2.2. Demonstration of the Deliverable

Chapter 1: Key Indicators for decentralized investments strategies The significance and behavior of the different KPIs to evaluate centralized and decentralized investments strategies is demonstrated on the RE-Demo zone including an hospital and single as well as multi family buildings with different renovation standards. Results show the importance of appropriate system boundaries, the need of hourly resolution of emissions values related to the grid, and the increasing attention which needs to be devoted to the grey energy connected to modern energy systems. Correlation of different key performance indicators are revealed to ease the process of decision making.

Chapter 2: Long term investment planning methodology A long-term planning method is demonstrated on a hospitals complex. The results can similarly be extended to the hospital in the RE-Demo district. The energy integration of new centralized and decentralized equipment is evaluated on a monthly basis over four periods until the year 2035.

The results show that, among the four investment scenarios identified, the most optimistic alternative allows to decrease the final energy consumption of around 36%, cut the CO_2 emissions by a half, multiply the renewable energy share by a factor 3.5 while reducing the annual total cost by 2 4%. This scenario considers mainly the integration of a very low temperature district heating with decentralized heat pumps to satisfy the heat requirements below 75°C, as well as heat recovery systems and the refurbishment of about 33% of the building stock.

Chapter 3: Investment in Grid-Aware Layout of photovoltaic panels The study, applied to the RE-DEmo test case, confirms the relevant influence of PV panels' azimuth and tilt on the performance of building energy system (BES). Whereas south-orientation remains the most preferred choice, west-oriented panels better match the demand when compared with east-oriented p anels. Apart from the benefits for individual buildings, an appropriate choice of orientation was shown to benefit the grid: rotating the panels 20° westwards can, together with an appropriate scheduling of the BES, reduce the peak power of the exchange with the power grid by 50% while increasing total cost by only 8.3%.

Chapter 4: The future digitalization of smart grids In this study, a new taxonomic framework has been developed starting from a general analysis of the emerging solutions, identifying intersectoral synergies and limitations with respect to the 'smart grid' concept. Finally, from the scenario portrayed, a set of issues involving engineering, regulation, security, and social frameworks have been derived in a theoretical fashion. The findings are likely to suggest the urgent need for multidisciplinary cooperation to address engineering and ontological challenges gravitating around investments in the smart grid concept.

3. Impact

Our objective within the REel demo project has been to develop urban energy planning methods to make recommendations for the integration of renewable energy in complex energy system. This works is done in the context of the work package 1 - Subtask 1.4 *Regional multi-energy grids - Planning Strategies for Distribution Grids and Multi-Energy Systems.*

Inline with the strategy presented in Chapter 4, p.38, industrial partners has commissioned a study to evaluate the feasibility of a heating and cooling district network (DHC) in the RE-Demo zone.

4. Chapter 1: Key Indicators for decentralized investments strategies

This chapter is drawn from the article of Middelhauve, Santecchia, Girardin, Maréchal and Margni, "Key Performance Indicators for Decision Making in Building Energy Systems" [6].

Policy makers and energy operator have the responsibility to select indicators for their mission to lead the renewable energy transition ensuring energy independence and security of supply in the context of decarbonisation of the energy mix and and/or nuclear phase-out with increasing cost for flexibility.

Engineers are therefore asked to propose key performance indicators (KPI) allowing to quantify the positive impact of operation strategies and efficient technology solutions to harvest and distribute more renewable resources, while minimizing the environmental impact and overall costs. The aim of this study is to analyze the impact of KPIs and their different definitions on planning building energy systems (BES) in order to support decision maker to define the best investment strategies when prosumer apacities are increased in the grid.

A wide-range of alternative solutions are generated using Mixed Linear Integer Programming (MILP) and Multi Objective Optimization (MOO) to capture the decision space of BES. Machine learning techniques, like principle component analysis and k-medoids clustering, are applied to identify the major trends, thus supporting multi–criteria decision making.

Results highlight the correlations between thirty-one indicators, showing the importance of (i) setting appropriate system boundaries, (ii) using hourly resolution and (iii) constructional footprint to characterize flexible systems. Low emission electrical grid mix has a high impact on strategic planning and is in conflict with decentralized, self-sufficient energy systems. Including life cycle assessment (LCA) of the system shows besides operational emission, the constructional footprint is significantly contributing to the total Global Warming Potential (GWP). Considering the ecological optimal BES in Switzerland, this contribution is more than 40%, while for high emission electrical grid mix the latter accounts for more than 90%.

4.1. Objectives and Method

The objective is to evaluate key performance indicators of building energy systems to assist the decision making. To identify a decision space, an MILP optimization approach is adopted, where the types and sizes of the different components of the BES are considered as optimization variables. Furthermore, MOO is performed with environnemental, economical, technical and security indicators as objective.

Heating requirements can be satisfied by an air-water HP, CHP,EH and a BO. Energy is stored in either stationary BA, domestic hot water and buffer STO or the building envelope. PV panels act as renewable energy sources. The different energy systems are interconnected to the main energy distribution networks: the natural gas, electricity and fresh water grid.

Three types of energy demands are considered: SH, DHW, and electricity. Electric load and DHW profiles were generated using standardized profiles according to Swiss norm [10].

The SH demand is impacted by factors such as the conductive heat losses through the building envelope, the heat capacity of the building and the heat gains from occupants, electric appliances and solar irradiation. Furthermore, space heating demand is characterized by the desired comfort temperature of the rooms and the nominal temperature of the heat distribution system [11].

The bulk of the modeling and optimization approaches employed in this paper are derived from [2], to which the reader is referred to for additional details. The MILP model is formulated in A Mathematical Programming Language (AMPL) and solved with the commercial solver cplex (version 12.9.0.0). In the following, variables are written in bold, parameters in normal characters. Considered periods in days are presented by the set P, while the number of hours in a period is given by the set T.

4.2. Key Performance Indicators

The environmental, economical, technical and security Indicators used as objectives are reported in Table 1. The detailed formulation of the indicators can be found in [6].

Environmental Indicators

There is a great variety of KPIs to determine and rate ecological performance of energy systems in open literature. Some are collected and presented in the review [12]. The focus of this study are energy systems for residential buildings. Therefore, the categories are reduced to GWP and the use of renewable energy sources.

Global Warming Potential The intergovernmental Panel on Climate Change (IPCC) refers to emissions as CO_2 equivalent [13]. Table 2 displays yearly average values of the profiles derived from the method from Kantor et al. [14] and the database "ecoinvent" provides LCA results of the different technologies [15].

The GWP of the building energy system $\mathbf{G}^{bes}$ is linearised in Equation 1. Where y is the binary decision if the technology is installed, f^u the unit size and l^u the unit lifetime. Table 3 is summarizing the associated impact factors i^1 and i^2.

$$\boldsymbol{G}^{bes} = \sum_{u=1}^{U} \frac{1}{l^u} \cdot \left(i^{g1,u} \cdot \boldsymbol{y^u} + i^{g2,u} \cdot \boldsymbol{f^u} \right) \tag{1}$$

Table 3 is summarizing the impact factors used to compute the Global warming potential of energy technologies.

When investigating the ecological footprint, commonly the greenhouse gas emissions per unit of final energy are considered [16]. In this approach, the footprint of batteries and thermal storage cannot be considered and additionally, the impact factors are based on different conversion efficiencies and

Type	Symbole	Desctiption	Unités
Economical	CAVE	Cost of Avoided Emission	CHF/kgCO_2
	Cop	Annual Cost of Operation	CHF/m^2yr
	Ccap	Capital Cost	CHF/m^2yr
	Cinv	Annual Cost of Investment	CHF/m^2yr
	Crep	Annual Cost of Replacement	CHF/m^2yr
	Ctot	**Total annual Cost**	**CHF/m^2yr**
	AR	Annual Revenues	CHF/yr m^2
	LCoE1	Levelized Cost of Electricity (Definition 1)	CHF/kWh
	LCoE2	Levelized Cost of Electricity (Definition 2)	CHF/kWh
	NPV	Net Present Value	CHF
	IRR	Internal Rate of Return	-
Environn -emental	G_op_av	Global warming potential from operation using average emission profiles	gCO_2eq/m^2yr
	G_op_dy	**Global warming potential from operation using dynamic emission profiles**	**gCO_2eq/m^2yr**
	G_op_ob	Global warming potential from operation used in the objective	gCO_2eq/m^2yr
	G_bes	Global warming potential from the construction of the Building Energy System	gCO_2eq/m^2yr
	G_lca1	Total Global Warming potential (Life Cycle Assessment)	gCO_2eq/m^2yr
	RES	**Renewable Energy Share**	**-**
	PVP	PhotoVoltaic Penetration	-
	CPbt	Carbon Payback time (only PV)	yr
	CPbtBA	Carbon Payback time (PV + BAttery)	yr
	AVE	AVoided Emission	kgCO_2/m^2yr
Security	SC	Self Consumption	-
	SS	Self Sufficiency	-
	GM	Grid Multiple	-
	GUd	Grid Usage demand	-
	GUs	Grid Usage supply	-
	PVC	PhotoVoltaic Curtailment	-
Technical	eta_1	Energy Efficiency (1st law efficiency)	-
	eta_2	**Exergy Efficiency (2nd law efficiency)**	**-**
	eta_1PV	Energy Efficiency (1st law efficiency) PV included	-
	eta_2PV	Exergy Efficiency (2nd law efficiency) PV inluded	-

Table 1: Performance indicators and it's reduction to four characteristic KPI's using PCA (§4.3, p.17).

Table 2: Global warming potential and Renewable energy factors related to the grid [14].

	Global Warming Potential	Renewable Energy Share
Electricity mix Switzerland	0.134 kg_{CO2}/kWh	0.42
Electricity mix France	0.072 kg_{CO2}/kWh	0.20
Electricity mix Poland	0.933 kg_{CO2}/kWh	0.13
Electricity mix Germany	0.508 kg_{CO2}/kWh	0.40
Natural Gas	0.214 kg_{CO2}/kWh	0

amortization cannot be compared to the unit choices. This would impose a rather large uncertainty. Thus we propose a different approach which divides the GWP into share coming from the Operation G^{op}

Table 3: Global warming potential to the construction of energy system technologies [15].

Technology [r]	Impact factor i^{g1} $[kg_{CO_2}]$	Impact factor i^{g2} $[kg_{CO_2}/r]$
Batteries [kg]	0	7.8106
Cogeneration unit [kWe]	460.55	0
Electrical Heater [kWth]	2.04	0.41
Gas Boiler [kWth]	253.27	11.62
Heat Pump [kWe]	0	138
Photovoltaic Panels [m^2]	0	78.711
Thermal storage [m^3]	0	1204

and the construction of the building energy system G^{bes} to derive the annual global warming potential G^{lca}.

Renewable energy share The renewable energy share (RES) gives the information to which part renewable energy sources are used to provide the required energy supply. Table 2 displays the average share of renewable energy from the electricity and gas grid. Additionally, to the grid supply the generated electricity on site from PV panels is considered to be 100% renewable.

PV Penetration The PV Penetration (PVP) measures how much of the total electricity demand of the building and the units could be covered by generated electricity from photovoltaic panels.

Economical Indicators

Annual Operating Expenses Annual OPEX comprise of the different energy exchanges with electricity (E) and gas network (H) to the connected tariffs (c_p).

Present Capital Value The present capital value is consisting of the investment cost and the replacement costs of the utilities with different expecting lifetimes [17].

Total Annual Expenses The Capital Recovery factor [17, Ch. 9] give the total annual expenses $\boldsymbol{C}^{tot}$. The capital recovery factor is the discount factor to transfer the present value of the capital to annual payments with respect to the project horizon n and the project interest rate i.

Net Present Value The NPV is the absolute value of the investment in the present, not evaluating the runtime of the project. Several studies use NPV to evaluate the investment plan into energy systems [18, 19] considering $C^{op,0}$ as the current annual OPEX without investment into new utilities [17, Ch. 10].

Internal Rate of Return The internal rate of return (IRR) is the discount rate to which the NPV would become zero, which means the higher the IRR the better and safer the investment. In contrast to NPV the IRR respects the runtime of the project and is not an absolute value. For example [20] use the IRR as objective to analyse the optimal PV size.

Annual Revenues The annual revenues (AR) accounts the benefit for selling the generated electricity to the grid and avoiding electricity import. In this study, electricity can be generated by CHP and PV panels, hence their operation is the only one considered. SC is the share of generated electricity which is self consumed.

Levelized Cost of Electricity I The definition of LCoE is controversial and therefore included in different versions. The first version (LCoE^{I}) is balancing the cost of the electricity generated onsite. If LCoE^{I} is a positive value, the investment of BA and PV is profitable. LCoE^{I} is only considering the generated electricity and the investment from PV panels and batteries. Including CHP in the calculation would neglect combined heating services. The performance indicator is defined according to the review [21].

Levelized Cost of Electricity II Another definition of the LCoE is applied by [19]. Instead of evaluating the electricity cost of a utility, this definition evaluates the electricity cost of the whole project. However, this definition is only applicable for systems without CHP and heat services based on electricity .

Technical performance Indicators

Energy efficiency The energy efficiency is the effectiveness of the system or the application of the first law of thermodynamics [22].

Exergy efficiency Exergy efficiency is evaluating the thermodynamic performance of the system respecting the second law of thermodynamics [22, 23]. A typical value for chemical exergy of natural gas is available in The exergy content of the heat demand $E^{Qbui,-}$ is consisting of domestic hot water at 328K and desired space heating at 293K. Reference temperature for the Carnot factor is the external temperature.

Security Indicators

The following performance indicators evaluate the security of the supply. Parameter of this category assess the autonomy like self sufficiency as well as parameter which protect the supply by measuring the impact on the grid.

Self Sufficiency Self Sufficiency (SS) is the ratio of the onsite generated electricity consumption to the total electricity demand [24].

Self consumption Self consumption (SC) is the share of the generated electricity which can be consumed onsite [24].

Grid Usage The Grid Usage (GU) gives the interaction with the grid in respect to the maximum uncontrollable load of the building. This is excluding heating as it is to evaluate the impact of a total system design on the grid[19].

PV curtailment The PV curtailment (PVC) factor is the total amount of PV energy that is curtailed from the PV generation.

4.3. Centralized versus decentralized investments in the Grid

Impact of System Boundaries

The considered system boundary is influencing not only the absolute values but also the relative trend of the performance indicator. Two examples are presented in the following.

Energy efficiency of solar PV The first example is demonstrating the different use of exergy efficiency. Studies focusing on the energy conversion of solar irradiation commonly use an average temperature of the sun around 6000K to determine the exergy efficiency of the system [25, 26]. In contrast, other studies exclude the solar irradiation from the exergy efficiency and directly balance the exergy generated from the solar system. Figure 1 compares both definitions with respect to the RES and total annual costs of different energy system configurations. For comparability reason, system solutions using natural gas are excluded and buildings with similar renovation states integrated. For electrical systems

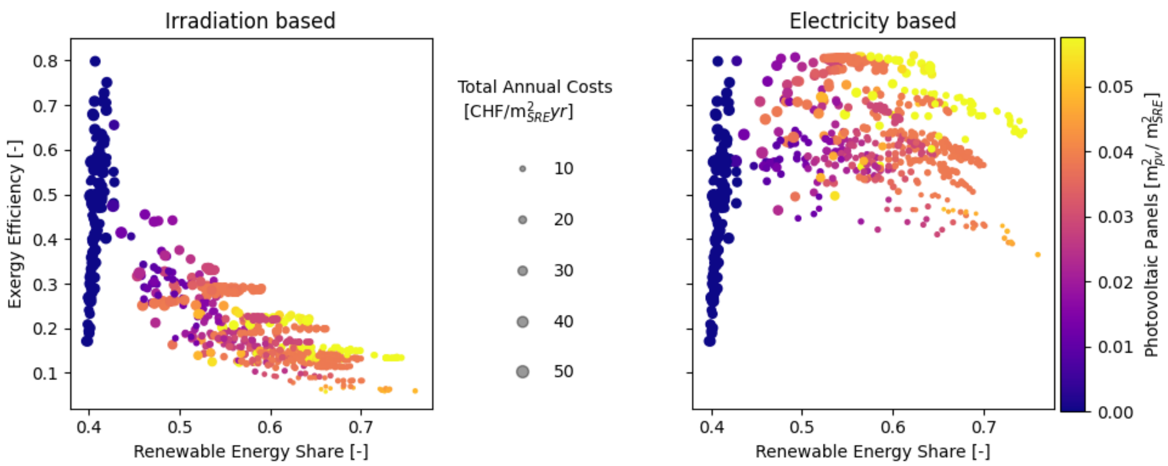
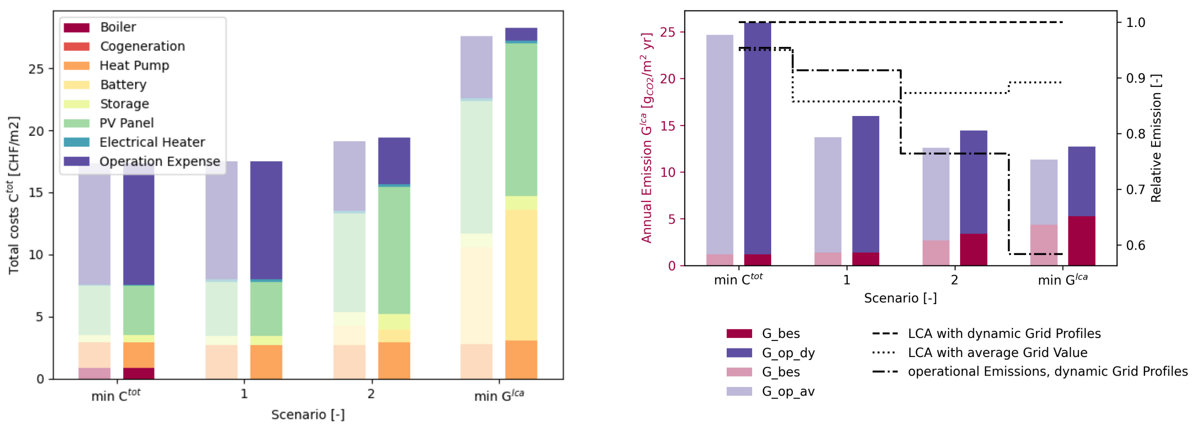


Figure 1: Exergy efficiency and RES for different BES solutions,which consist of different sizes for installed HP, EH, PV panels, STO and BA. The capacity of installed PV panels is normalized by the energy reference surface (ERA) of each building. Comparison of two different definitions of exergy efficiency: on the left with exergy content of the environment (e.g. irradiation) and without (on the right).

without PV panels the RES is constant and the exergy efficiency is increasing when substituting electrical heater with heat pumps to satisfy heating demand. Increasing the share of PV panels, leads to an increase in RES and to very different behavior among the two versions of the exergy efficiency. The low exergy efficiency of the PV panels is decreasing the overall exergy efficiency drastically when balancing the solar irradiation. The exergy evaluation of different system configuration is dominated by the installed size of PV panels per heated surface in the latter case. Solar irradiation is free of charge and the exergy efficiency of the systems only interesting for developing the solar system itself. For the evaluation of building energy systems we therefore recommend to exclude the exergy efficiency of PV panels. If the irradiation is included into the exergy balance, the exergy efficiency for generating the electricity on the grid should also be included to lead to comparable results.

Constructional footprint of decentralized energy systems The second example is demonstrating the importance of appropriate system boundaries when evaluating the GWP of energy systems. Considering only green house gas emission during operation of the systems is leading to 10% too little emission for the low cost scenarios (see Figure 2b). However, increasing the renewable share by removing natural gas and establishing the system on solar - battery combination decreases the operational emission but increases the footprint of the construction of the system. Neglecting the constructional emissions causes an annual error of more than 40% for systems with the lowest total emission.



(a) *(b)*

Figure 2: The trade off between (a) total annual costs and (b) emission for planning of building energy systems. MOO of a typical Swiss building effected from average emission values of Swiss grid mix (light) and dynamic profiles (dark). Scenario 1 and 2 are intermediate Pareto optimal solutions.

Impact of the sampling periods

The impact of the resolution of the input data is discussed in a broad range of papers and from various perspectives. Especially the resolution of weather and demand data is content of extensive research.

This work presents a novel aspect, the resolution of the electrical grid mix. Figure 2 shows the comparison between yearly average value and hourly profiles during multi objective optimization of total costs and global warming potential. Since the grid mix is high on emission during winter days as well as the heating demand, the emissions are in general underestimated by around 10% when assuming an average value. Furthermore, different energy system configurations are identified to be optimal in emissions. The increase of self consumed electricity in winter months has a higher priority, thus PV systems and batteries are chosen to a greater share.

Impact of the energy transition horizon

The grid mix has a high impact on the solutions. It influences not only the decision making of single energy systems but also reveals different national strategies. Next to the weather, which is determine the demand or the solar potential, the grid mix of different countries impacts the solution. Table 2 displays yearly average values of the profiles derived from the method from [14].

Figure 3 shows different optimal energy system configurations for a single residential building in four exemplary different European countries. For countries with high emission mix on the grid, the best

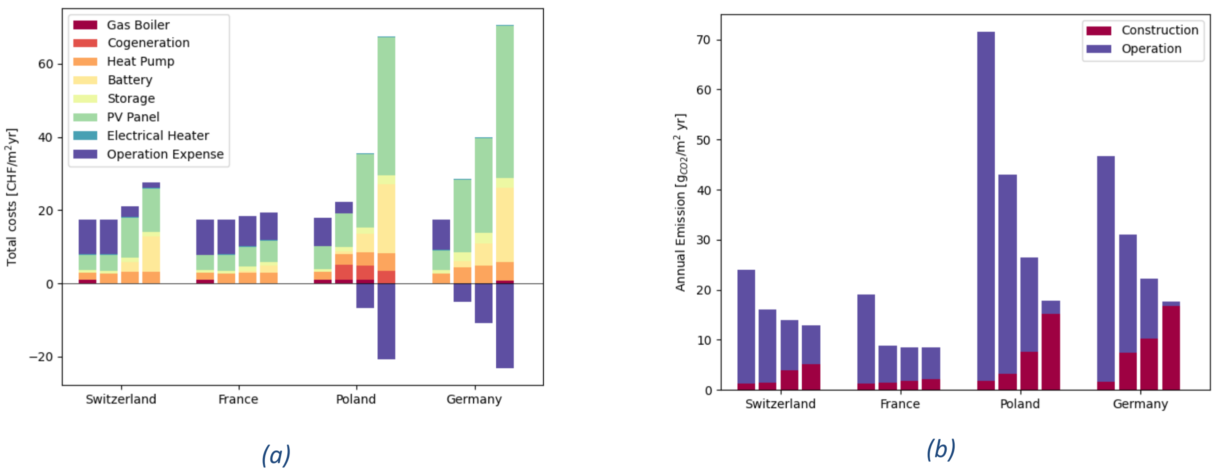


Figure 3: Comparison of different energy system configurations for a typical residential building in four European countries. Four Pareto optimal points between (a) total annual costs and (b) annual emission for each country.

solutions consist of decentralised generation, taking into account the high constructional footprint of technologies like PV panels and batteries. For countries where the GWP of the electricity exceeds the potential of burning natural gas, it is even suggested to invest in to decentralised cogeneration technologies like solid oxide fuel cells.

Next to the geographical context, this example can also be understood as the demonstration of the impact of the project horizon. The project horizon is considered to be 20 years, a time period in which the grid mix is almost certain to change, in context of the energy transition towards a less polluted electricity mix. In this situation, it would be more profitable for both annual emission and cost, to use the electricity from the grid instead of decentralized production.

Principal component analysis

The aim of the next section is to explore the decision space and support the multi criteria decision making. Over 8000 different solutions are generated by considering each indicator in a multi parametric optimisation framework. The correlation between the different indicators is demonstrated by performing a principal component analysis in the decision space. Figure 4a shows the correlation plot of the KPIs in the first two dimensions from the principal component analysis.

The distance to the origin measures the quality of the indicator and its contribution to define a solution. Strongly correlated indicators are grouped together, for example G^{bes} and C^{inv}. This correlation due to the fact that the highest environmental footprint of the system have batteries and PV panels, which are also the most expensive units. It confirms the previous statement to Figure 2b, for more expensive system configurations, which usually consist of a larger share of PV and battery, constructional emissions cannot be neglected. Similar is the correlation can be observed between the OPEX (C^{op}) and the GWP of the operation (G^{op}). Main contributor to both OPEX and operational GWP of is the fuel and electricity imported by the system. However, the vectors are not as close as the previous example due to the high GWP of natural gas compared to the electricity (compare Table 2) but the inverse correlation of cost (1:2.5) in Switzerland.

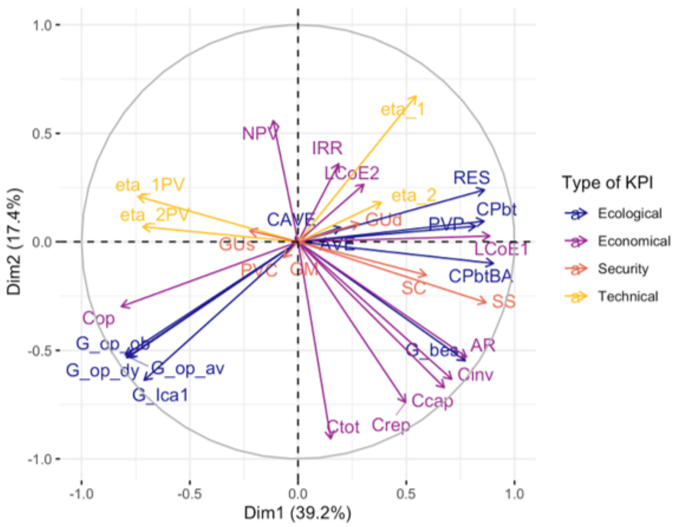
In Figure 4a, inverse correlated KPIs are opposite to each other. One example is the correlation of NPV and total costs (C^{tot}). The higher the total cost of the proposed energy system, the lower is the net present value of the system. Current OPEX play a minor role in this context.

The value of these results is two-fold: On one hand it reveals the redundant indicators. Therewith, it supports the decision maker to select a subset of essential indicators. On the other hand it shows the indicators which contribute the most to define a solution and should not be neglected. The impact of these results are demonstrated in the following. Typical solutions are derived by performing a k-medoids clustering of the more than 8000 different MOO solutions for the 44 buildings of the case study. A subset of uncorrelated indicators are then used to evaluate the performance of the typical systems. Figure 4a presents the result.

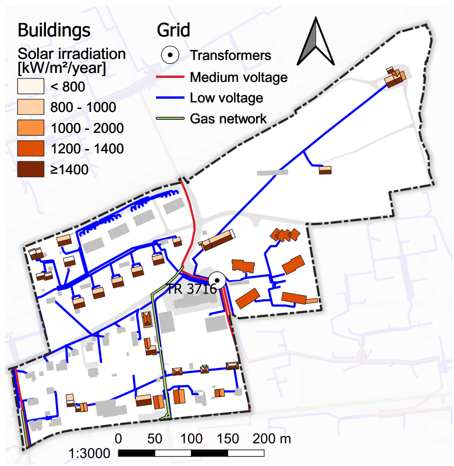
A particular striking solution in Figure 5 is medoid one. The system is based on natural gas boiler, the GWP of the operation is highest and the RES lowest among the other medoid solutions. Figure 4a shows that GWP and costs of the operation as well as RESand SSare correlated. So it can be concluded that the OPEX are high and the SS is low of system one. In contrast is solution four which has a high share of HP, PV, BA and thermal STO. The latter two account for lower exergy efficiency while the whole configuration is low in GWP of the operation. With Figure 4a one can conclude that the OPEX of system four a low as well. In comparison to the other mediods the total annual cost are the highest. This leads to the conclusion that the investment costs are high as well.

subsectionConclusion

This work addresses different sensitive points regarding the definition of the indicators:



(a)



(b)

Figure 4: a) Variable correlation plot of the principal component analysis. Positive correlated KPIs are grouped together, not correlated are perpendicular, inverse correlated are 180° opposite. Distance from the origin gives the impact of the KPI itself. b) Map of case study district in Rolle, Switzerland.

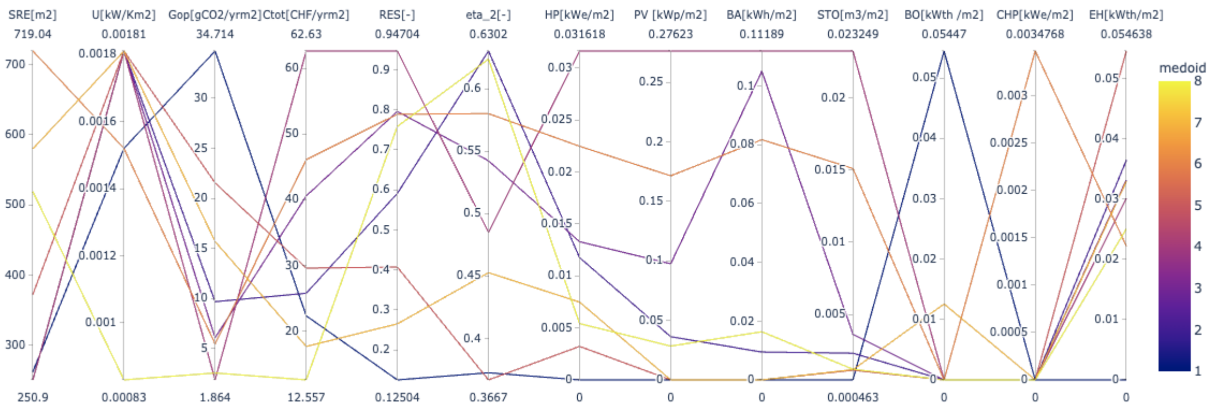


Figure 5: Result of K- medoids clustering of the technology decisions within the 8000 different MOO solutions for 44 residential buildings. Visualized building related parameter are the heated surface [m^2] and the heat transfer coefficient U to describe the renovation state[11]. Four uncorrelated KPIs are selected (see Figure 4a).

- Including the solar irradiation into the calculation of exergy, disadvantages solar based building energy systems and should therefore either be excluded or considered together with the whole exergy efficiency of the grid mix as well (i.e including power plants);
- while the constructional emissions of the existing energy system might be neglectale (smaller than 5%), the situation changes drastically for modern, decentralized systems, where the footprint can account for more than 40%;
- the grid mix has a great impact on the investment strategy. High carbon content of the grid favors the development of decentralized energy systems, while low carbon content conflicts with the

development of self-sufficient decentralized energy systems;

- considering annual average values of the grid mix is underestimating the GWP of around 10%, since energy demand in buildings is highest in winter where the associated GWP to the grid mix is larger. If the energy system evolves towards decentralisation, using hourly value will become necessary for proper evaluation of environmental indicators. Indeed, considering hourly grid mix favors self-consumption in winter with the emergence of batteries/PV solutions;
- Accounting emission with a short term horizon of 20 years favors the actual grid energy mix rather than decentralization.

Therefore, the decision-making process needs to be tied to a long-term planning cycle. Chapter 2 presents a method to integrate multi-energy urban systems in a long term investment perspective.

5. Chapter 2: Long term investment planning methodology

This chapter is drawn from the article of Bornand, Girardin, Belfiore, Robineau, Bottallo and Maréchal "Investment Planning Methodology for Complex Urban Energy Systems Applied to a Hospital Site" [7]. The case study of this work is very similar to the RE-Demo test case with an Hospital - big energy consumer - which might become a magnet for investments in the development of decentralized district multi-energy system.

To achieve effective energy transition towards renewable energy systems, the decision-making process needs to be tied to a long-term planning cycle integrating the life-cycle of buildings and building systems [27]. The crucial point here is that the selection of investment scheduling strategies are shaping the energy future of the community for at least the next 25 to 50 years [28]. However, as the use of energy-efficient equipment and renewable energy technologies requires a higher initial investment than ordinary equipment and longer payback time [29], the commitment to long term investment is disfavored by the current context of low energy prices.

The current work contributes to the long term needs characterization, heat recovery potential and resource availability assessment of major energy consumers, with the final goal of improving their integration within the urban sector, optimizing the mesh of energy flows at the district scale and properly scheduling the investments.

5.1. Investment scheduling in energy planning

Multi-time optimization problems including investment scheduling have been formulated mainly in the purpose of helping expansion planning of factories assuming fluctuating market. [30] maximized the Net Present Value (NPV) assuming varying prices, while [31] proposed a multi-objective mathematical programming to select a portfolio of independent investments in the form of projects in a multi-planning period, with project parameters evolving through the time horizons. Recently, [32, 33] proposed an optimization approach using process integration and multiple investment periods for long-term industrial investment planning.

This work extend the methodologies above for the planning of complex urban energy system where capital expense and timing of implementation are the key components for the selection and deployment of technologies [34] . The proposed multi-period description characterize the main stages of the future district evolution by integrating refurbishment actions as decision variables of the optimization problem, thus allowing to plan improvement of the building envelope and hydronic system.

5.2. Materials and methods

The proposed approach extends the use of process integration techniques to the generation of long-term energy strategy and investment planning for heterogeneous and evolving major energy consumers. Building thermal modeling techniques and state-of-the-art optimization approaches are combined and applied to a complex hospital district whose processes are subject to high hygienic and supply reliability constraints.

The overall demand of the hospital complex is defined by the combination of characteristic processes, based on the results of a first stage of data monitoring and analysis, and space heating/cooling estimated through the building thermal model. In order to apply energy integration techniques on evolving systems, the power heat load ($\dot{Q}$) and temperature levels (T) of all streams must be assessed in the form of composites curves ($\dot{Q}_{p,h}, T_{p,h}$) for typical operating periods of a year (p) over several long-term temporal horizons (h).

As space heating, cooling and ventilation account for about one third of the final energy consumption for hospitals located in central European climate (Table 4), assessing the retrofit potential of the building envelope and HVAC systems is a primary concern.

Finally, parametric optimisation is employed to generate alternative scenarios, whose major underlying trends are identified through clustering techniques .

Integrating the property master plan

The Property as well as urban projects master plan define time constraints related to technology availability and renovation potential within the year 2035. The considered 20 years long term projection is thus divided into 4 time horizon of 5 years. The Property master plan foresees the full renovation of the district south zone while considering partial service restructuring in the north zone. These projects can be seen as an opportunity for envelope refurbishing, and the relevance of such actions are assessed and optimized for the north zone group of buildings (orange marked entities, including 5A and 6A). Urban energy supply projects such as 4thgeneration very low temperature DHC which are emerging in the hospital area are also included to assess the profitability of integrating them in the project.

Table 4: Yearly final energy balance of the hospital district (source: HUG, 2015).

Supply sources		Services	
Gas and fuel oil	51%	Space heating	24.6%
		Process	13.0%
		Unidentified (losses and other)	13.4%
Cooling network	12%	Space cooling and dehumidification	5.3%
		Cold process	6.3%
Grid	37%	Refrigeration units	3.6%
		Heavy medical equipment	4.6%
		Uncontrollable load	20.3%
		Fan	7.4%
		Sparse air conditioner and compressed air	1.5%

Long term investment scheduling

Investment scheduling aims at gradually replacing the existing facilities. The primary target influencing utilities selection and sizing in public buildings, especially hospitals, is reliability in energy supply and power load backup, as presented in the list of criteria defined by [35]. To ensure security of supply and redundancy, a risk analysis of failure scenario defined by energy supply blackout during extreme days (winter and summer) has been simulated resulting in the definition of availability constraint (Equation 2a and 2b) ensuring a minimum capacity for backup units ($\tilde{u}$) permanently installed on-site.

$$f_h^{\tilde{u}} = f_1^{\tilde{u}} \qquad \forall \tilde{u}, h \tag{2a}$$

$$y_h^{\tilde{u}} = y_1^{\tilde{u}} \qquad \forall \tilde{u}, h \tag{2b}$$

Moreover, the evolution of the Property master plan defines the set of temporal horizons. The changes are put in force by Equation 3a and 3b with binary parameters for construction ($a_h^b = 1$), demolition or replacement ($a_h^b = 0$) of buildings and availability ($a_h^u = 1$) or dismantling ($a_h^u = 0$) of equipment after the lifetime limit.

$$y_{p,h}^{b|u} \leq a_h^{b|u} \qquad \forall\, (b \text{ or } u), p, h \tag{3a}$$

$$y_{p,h}^{b|u} \leq a_h^{b|u} \qquad \forall\, (b \text{ or } u), p, h \tag{3b}$$

Additional continuity constraints could possibly be activated for some particular units (e.g. PV, DHC, etc.) to avoid selling and to ensure constant or increasing installed capacity in time until decommissioning

(Equation4a to 4c).

$$y_h^u \leq y_{h+1}^u \tag{4a}$$

$$f_h^u \leq f_{h+1}^u \qquad \forall\, u, h \leq n_h - 1 \tag{4b}$$

$$f_h^u - f_{h+1}^u \leq (y_h^u - y_{h+1}^u) \cdot f_{max}^u \tag{4c}$$

Multi-criteria decision analysis

The set of final system configurations (i.e. results from the last period 2030-35), obtained through the parametric optimization, is clustered using k-medoids algorithms and elbow's method. It allows for identifying the existing solution representative of the cluster. The scenarios identified by the cluster medoids define the main investment strategy trends and are represented by a parallel coordinate plot (Figure 7).

The last period is considered for defining the KPI of each solution to assess the relevance and effectiveness of the energy performance actions. The considered KPI are the following: final energy consumption, renewable energy share, CO_2 emissions, annualized operating and investement costs.

5.3. Results

Scenarios towards the best long term energy planning

The mix of solutions generated by the parametric optimization form a Pareto front as depicted in Figure 6. The parallel plot (Figure 7) shows each solution features in the last time horizon with the four scenarios highlighting the major trends.

Values of the objective function and the KPI are expressed per year and ERA in order to compare the different time horizons. The last time horizon (2030-2035) is taken as reference in order to assess the indicator's quality (Table 5).

Table 5: ERA relative indicators increase between 2015 and 2035.

	2015 values	Scenario 1 [%]	Snenario 2 [%]	Scenario 3 [%]	Scenario 4 [%]
Yearly final energy consumption	302 [kWh/m^2/y]	-32	-38	-36	-32
Yearly CO2 emissions	52 [kg-CO_2-eq/m^2/y]	-76	-73	-60	-42
Annual total cost	34 [CHF/m^2/y]	+3	-20	-24	-27
Renewable energy share	20 [%]	-20	+155	+255	+150

Scenario 1 is characterized by the full refurbishment of the whole building stock in the north zone (65% of the total ERA refurbished, Figure 7), leading to a large increase in the expenditures (34% higher than scenario 2, the second most expensive). This scenario maximizes the use of SOFC fuel cells for co-generation

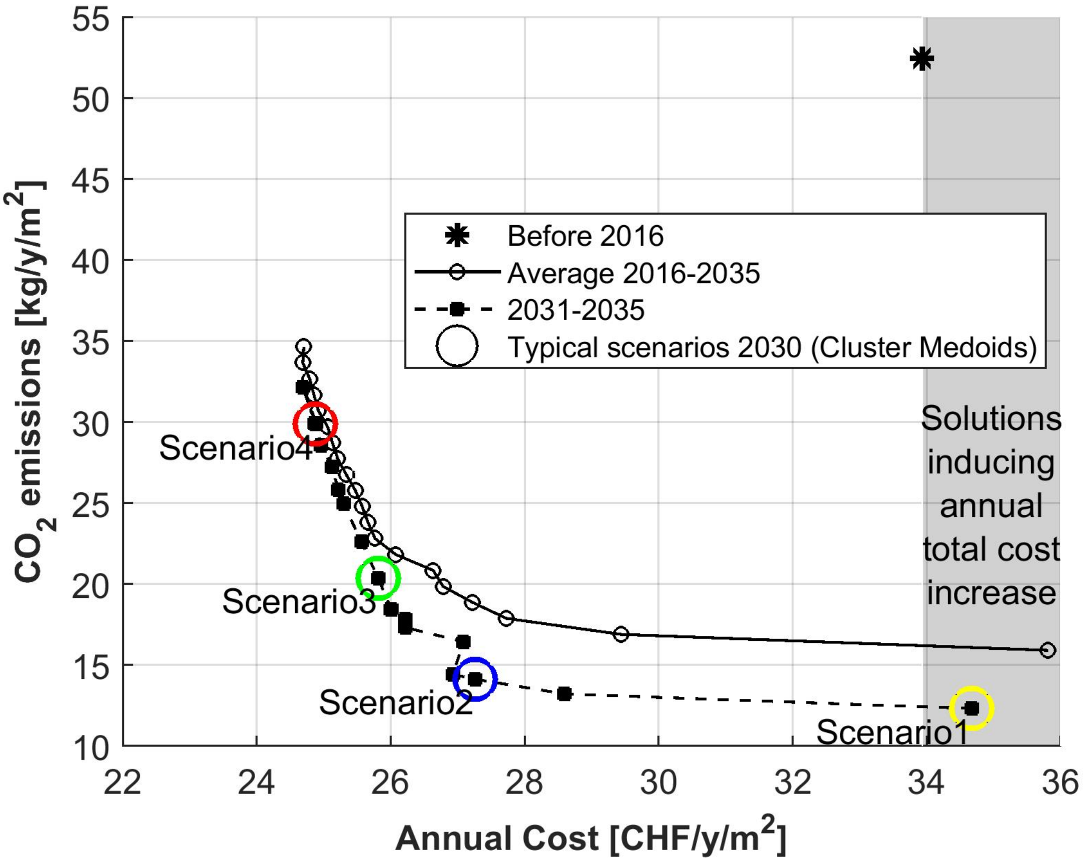


Figure 6: Pareto front resulting from total costs minimization under constrained CO_2 emission level. The 4 cluster medoids are extracted horizon (2031-2035). The medoids are set as reference solution for generating energy planning scenarios. The average correspond to the sum over the 4 horizons between 2016 and 2035 devided by 20 years.

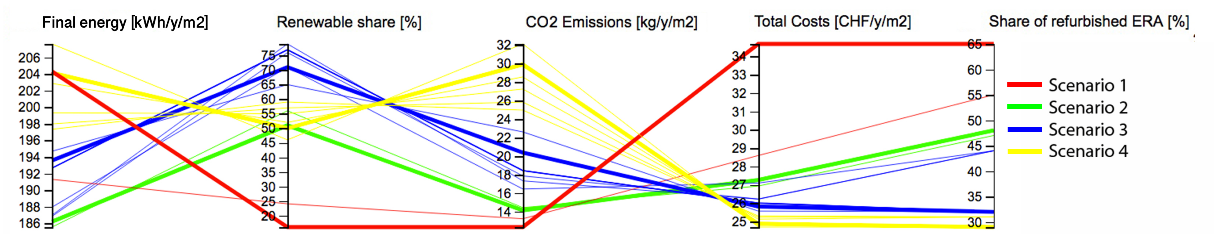


Figure 7: Mix of solutions (20 lines aggregated according to the colors of Figure 6), the 4 scenarios extracted thanks to k-medoid algorithm (bold lines) and the corresponding KPI for time horizon 2030-2035.

purposes, which is associated with a large natural gas consumption increase and a low renewable energy share (Figure 7).

Following the State prescriptions in terms of final energy consumption and renewable energy share, scenario 3 appears the best option, allowing 36% final energy consumption reduction, while reducing

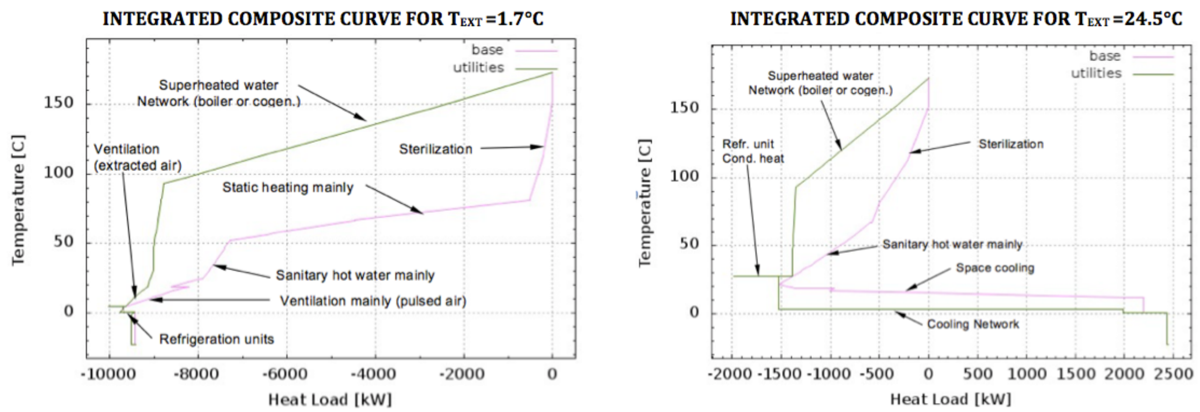


Figure 8: Integrated Composite Curves (ICC) in current configuration (2015) for two typical wintertime and summertime operating conditions with average external temperature of February (1.7°C) and July 2015 (24.5°C).

the CO_2 emission level by 60% and decreasing the annual total cost by 24%, considering full integration of all the thermal streams (Figure 8).

As highlighted by the parallel plot (Figure 7), very low emission level solutions (scenario 1) promote the sale of all conventional gas utilities (e.g. Boiler, Diesel engine) in 2020, assuming full refurbishment of the north zone (Figure 10). These units are replaced by low temperature utilities such as heat pumps, as well as solar thermal collectors and CHP SOFC units to fulfill high temperature needs (Figure 9).

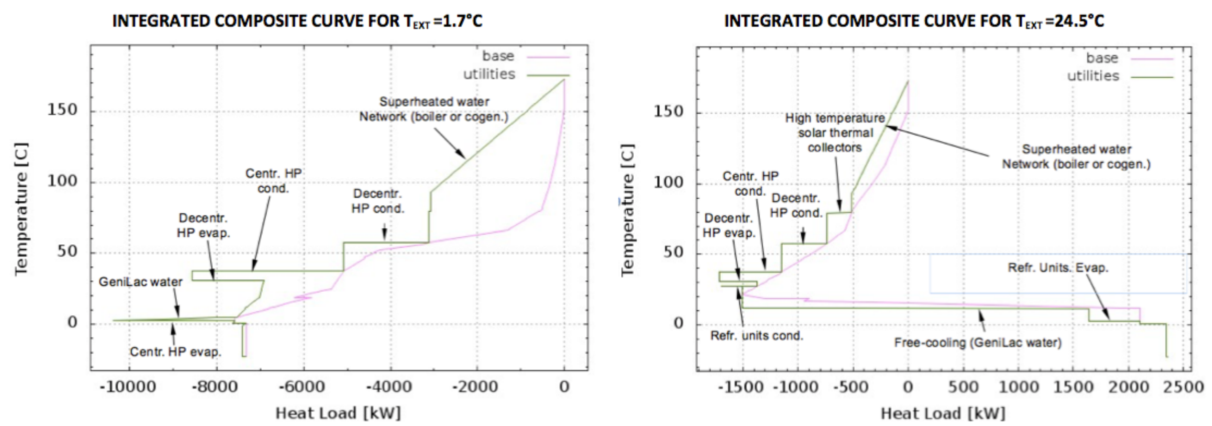


Figure 9: Integrated Composite Curve (ICC) for time horizon 2030-2035, for two typical wintertime and summertime operating conditions with average external temperature of February (1.7°C) and July 2015 (24.5°C), considering maximum refurbishment, multi-stage Heat pumps, solar thermal collectors and GeniLac DHC.

The other scenarios promote the use of reciprocating co-generation engines combined with SOFC fuel cell (scenario 2) or gas boiler (scenario 3 and 4) to supply high temperature demand. DHC is considered profitable for both heat pumping and direct cooling purposes in each scenario, the cost of this technology being assumed of 10 cts/kWh . Each scenario favors as well the installation of multi-stage heat pumps to satisfy heating needs below 75 °C, using the above mentioned DHC, together with the refurbishment of minimum 30% of the total ERA (Figure 10). As reference design value, about 2000 kW water supplied at 5°C is required to feed a centralized heat pumps of 4000 kW capacity, when external temperature is of 1.7°C.

As shown by the Integrated composite curves (Figure.9), all comfort cooling needs (4000 kW at 12 °C when the external temperature is 35 °C) are fulfilled by free cooling thanks to DHC. This network is moreover used as refrigeration unit hot source, for the purpose of satisfying lower temperature process needs.

The optimized investment planning (Figure.10) shows a transition period between 2016 and 2021, before the integration of DHC. Equipment sizes are furthermore subject to evolve significantly up to 2026 due to architectural morphing projects. Regarding the heat pumps, scenarios 1 to 4 promote the investment in low temperature heat pumps (5000 kW capacity in total supplying heat at 35°C), combined with medium temperature heat pumps (totalling 2000 to 3000 kW capacity at 55 to 75 °C).

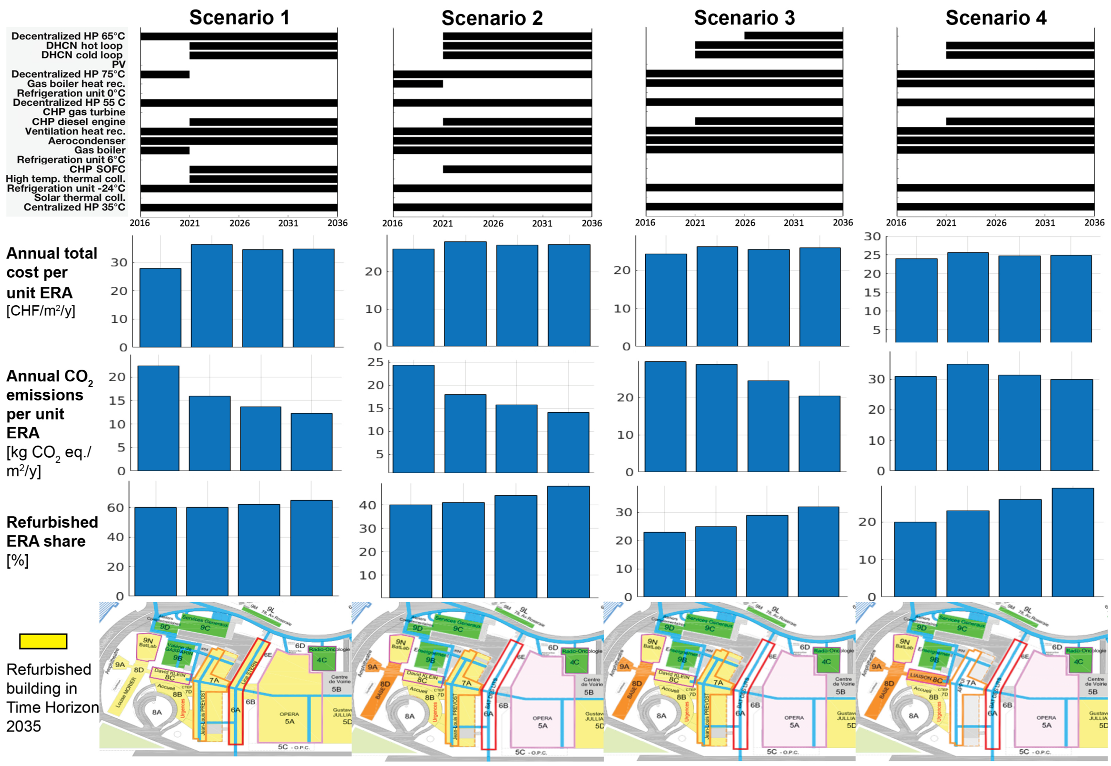


Figure 10: Optimized planning related to the investment in new energy supply units and building refurbishment actions, with associated total costs at each of the four time horizon. Comparison with CO_2 emissions level for each scenario. The Map of refurbishment actions aggregates all time horizons.

Towards the solution design

The proposed design (Figure 11) is a median option inspired by scenario 3, considering topology constraints specific to the case study. It is a modular solution, favouring the energy transition towards a step by step reduction of CO_2 emissions, as it allows for a progressive reduction of the gas utility resort, in phase with the building stock refurbishment. The heating needs are mainly covered by two stage centralized heat pumps with complementary gas boiler or CHP. The hot source of the cold production units is recovered by an intermediary hot loop at 17 $^{\circ}C$ used for feeding the heat pumps.

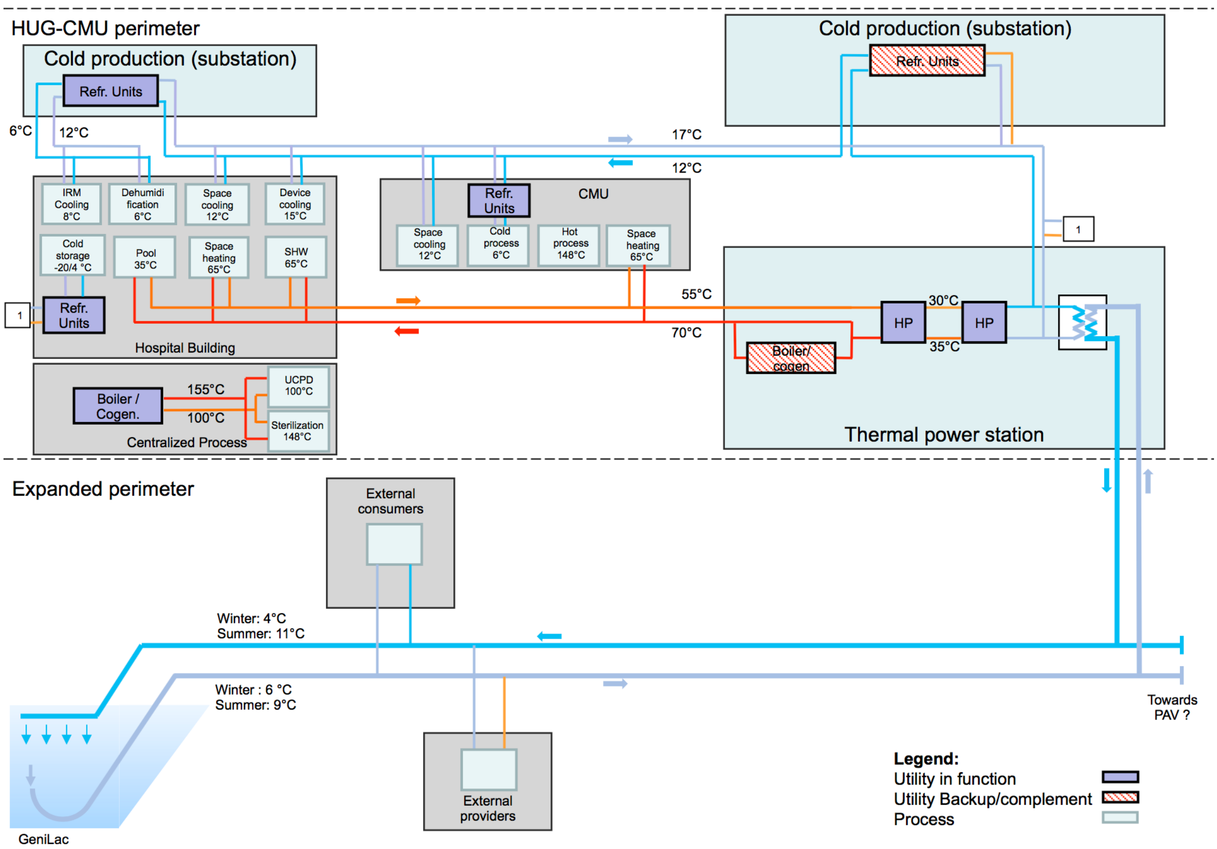


Figure 11: Proposed energy layout for time-horizon 2030-2035.

5.4. Conclusion

The results have shown that the implementation of a multi-time formulation coupled with parametric optimization appears as a powerful mean to generate integration strategies for those applications characterized by complex heterogeneous building stock and evolving demand. The authors have identified the following as the main reasons:

- The investment strategy can be staged to match the evolving demand and resource availability, taking into account the architectural morphing associated to the Property and State master plan.
- As half of the thermal needs of the hospital district are dedicated to space heating, while the

retrofit of the building envelope implies the highest expenditures, scheduling the investment is a central aspect. Results have shown that refurbishment appears as an action to be executed in early stages, with priority given to buildings with large aspect ratio (as roof refurbishment is very efficient and involves moderate costs), reducing both the heating thermal load and the supply temperature of the hydronic network. This consideration justifies the use of a model able to distinguish among thermal losses and air conditioning demand and to characterize evolving heating needs over the years.

- A simple post-processing analysis would allow to refine the investment strategy, for example including the installation of smaller units or transition solutions to facilitate the evolution among consecutive periods.

Moreover, the parametric optimization has been proven suitable to avoid further complexity of alternative multi-objective formulations, while successfully targeting the legal prescriptions (maximal CO_2 emission level, maximal energy consumption level). The final step would be the choice by the decision maker among the different strategies derived from the various scenarios generated by the clustering algorithm.

In the particular case study, the best mean for targeting the MER appears to be the implementation of heat recovery in the ventilation systems. The fresh air flow being generally oversized in old hospital building, the proposed model is suitable for buildings with global heating consumption monitored at a sampling time shorter than 24 hours. Only in this case indeed it would be possible to distinguish whether retrofitting actions are to be implemented on the ventilation system or on the building envelope and to estimate the potential benefit. Nevertheless, global static values can be easily extrapolated to other buildings of the same type with lack of energy consumption monitoring, knowing their geometrical parameters and age.

With reference to the State prescriptions in terms of maximal final energy consumption and minimal renewable energy share, very-low temperature DHC system (scenario 3) emerges among the set of solutions generated by the optimization routine, allowing 36% final energy consumption reduction while decreasing the annual total cost by 24%. This corresponds to the most optimistic scenario regarding the renewable energy share (current values multiplied by a factor 3.5), based on a full integration of all the thermal streams (i.e. introducing heat recovery systems) including the ventilation extracted air, with a total of 2000 kW air heat recovery systems to be implemented, the refurbishment of about 35% of the building stock, installation of 8000 kW multi-stage heat pumping and implementation of direct cooling through the DHC (7000 kWhydro-thermal network).

6. Chapter 3: Investment in Grid-Aware Layout of photovoltaic panels

This chapter is drawn from the article of Middelhauve, Baldi, Stadler and Maréchal, "Grid-Aware Layout of Photovoltaic Panels in Sustainable Building Energy Systems" [8].

In the context of increasing concern for anthropogenic CO2 emissions, the residential building sector still represents a major contributor to energy demand. The integration of renewable energy sources, and particularly of photovoltaic (PV) panels, is becoming an increasingly widespread solution for reducing the carbon footprint of building energy systems (BES). However, the volatility of the energy generation and its mismatch with the typical demand patterns are cause for concern, particularly from the viewpoint of the management of the power grid.

This paper aims to show the influence of the orientation of photovoltaic panels in designing new BES and to provide support to the decision making process of optimal PV placing. The subject is addressed with a mixed integer linear optimization problem, with costs as objectives and the installation, tilt, and azimuth of PV panels as the main decision variables. Compared with existing BES optimization approaches reported in literature, the contribution of PV panels is modeled in more detail, including a more accurate solar irradiation model and the shading effect among panels. Compared with existing studies in PV modeling, the interaction between the PV panels and the remaining units of the BES, including the effects of optimal, scheduling is considered. The study is based on data from a residential district with 40 buildings in western Switzerland. The results confirm the relevant influence of PV panels' azimuth and tilt on the performance of BES. Whereas south-orientation remains the most preferred choice, west-orientationed panels better match the demand when compared with east orientationed panels. Apart from the benefits for individual buildings, an appropriate choice of orientation was shown to benefit the grid: rotating the panels 20° westwards can, together with an appropriate scheduling of the BES, reduce the peak power of the exchange with the power grid by 50% while increasing total cost by only 8.3%. Including the more detailed modeling of the PV energy generation demonstrated that assuming horizontal surfaces can lead to inaccuracies of up to 20% when calculating operating expenses and electricity generated, particularly for high levels of PV penetration.

The main contribution of this study lies in the inclusion of different orientations of the PV panels in the MILP framework of the BES.

6.1. Method

An optimization approach has been developed adopted, where the types and sizes of the different components of the BES, and the size, azimuth and tilt of the PV modules, are considered as optimization variables. To this end, a robust and flexible modeling framework able to take into account the BES, solar based energy systems, and the impact of solar irradiation in an urban context is required. The modeling framework applied in this paper is based on the BES modeling by [2]. Instead of integrating PV modules solely based on global irradiation, oriented irradiation is included using the cumulative sky approach (Robinson and Stone, 2004) in combination with its integration into urban context [36]. The optimization of BES requires a time horizon of several years and therefore is a computationally intense task. To overcome this issue, it is necessary to reduce the amount of input data and select typical operation periods using machine learning techniques [37].

The modeling framework and its components are described in [8]. It is based on an Energy System Modeling Framework using MILP optimization formulation considering the oriented irradiation and shading effects between oriented modules

6.2. Results

The proposed method is applied first to a single a typical residential building and then extended to the RE-Demo case.

Multi-objective optimisation at building scale

The first study presents a typical residential building with a heated area of 250 m^2 and a large available roof area consisting of four tilted and one flat surfaces (see Table 1). For determination of the oriented shading losses between PV modules, the design limiting angle β is set to 20°, which represents the lowest Sun evaluation during solar noon for Geneva in Switzerland, occurring on the 21st of December [38]. This was chosen as an acceptable trade–off between space requirements and shading losses. Shading losses are below 10% for tilt angles between the horizontal position and those leading to maximum electricity generation. The results of the Multi-objective optimization (MOO) for the reference building are shown in Figures 12, 13.

The CAPEX and OPEX for each non-dominated solution on the Pareto front are shown in Figure 12A and are divided by the heated surface of the building to ease comparison. The CAPEX ranged from a minimum of 2.8 CHF/m^2 yr (Scenario 1) to 48 CHF/m^2 yr (Scenario 14), whereas the OPEX ranged from 1.9 to 24 CHF/m^2 yr. The scenario numbers (1–14) are defined as the points on the Pareto curve, ordered from the lowest to the highest CAPEX.

Although all scenarios are optimal from a Pareto perspective when looking at CAPEX and OPEX separately, the analysis of TOTEX tells a different story, as shown in Figure 12D:

Scenarios 1 through 9 The resulting TOTEX are similar in at around 27 CHF/m^2 yr (minimum TOTEX for Scenario 4–6 at 25 CHF/m^2 yr), whereas they increased rapidly in Scenarios 10–14, reaching a maximum of approximately 50 CHF/m^2 yr.

Scenarios 9–14 The increase in TOTEX is due to the fast increase in CAPEX in these scenarios, mostly due to the decision to install batteries (first appearing in Scenario 10), which is not compensated by a commensurate reduction in OPEX. The reason for this trend can be seen in Figure 12C: in Scenarios 3–8,

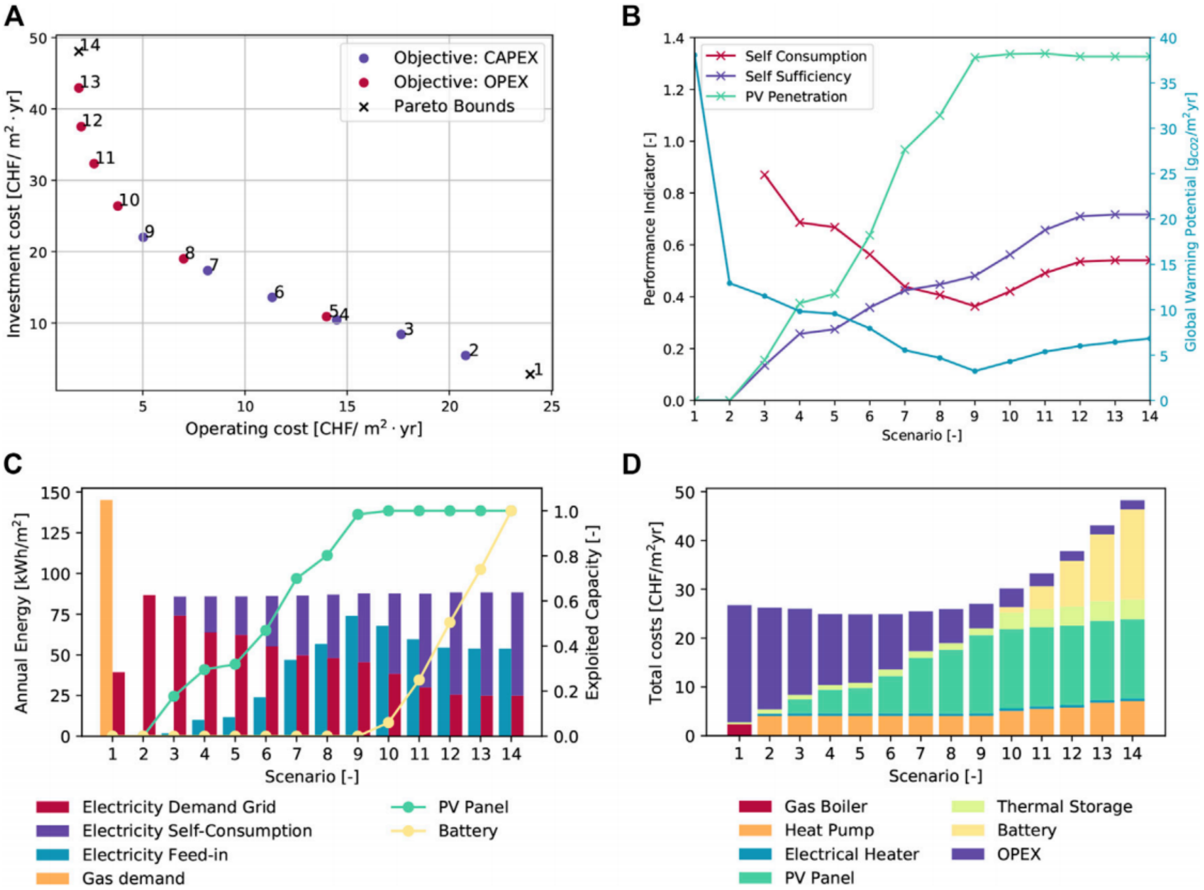


Figure 12: Results of MOO of one residential building: (A) definition of Scenarios on pareto curve for investment and operation costs, (B) performance indicator for each scenario, (C) usage of resources, and (D) distribution of total annual cost in identified energy system configurations.

the OPEX are reduced by installing PV panels, hence reducing the electricity demand from the grid, while gradually increasing the electricity feed-in. As the PV capacity saturates, OPEX can be further reduced by increasing the self consumption, because of the price difference between buying electricity from the grid and selling it to the grid. This can be achieved by installing batteries, which allows for a better match between demand and supply.

Scenario 9 to 14 Both the electricity demand from the grid and feed-in decrease, meaning that the total amount of energy generated locally remains approximately constant, but it is used for fulfilling the demand rather than sold to the grid.

This can be also observed from the evolution of SS and SC (Figure 12B). The SS gradually increases when the PV panels are installed, and continues increasing even as the PV penetration flattens, because of the use of batteries. On the other hand, the SC first decreases with increasing PV penetration (until Scenario 9), and then begins increasing again as a result of the use of batteries.

Figure 12B also shows the performance of the Pareto-optimal solutions in terms of GWP. The main contribution to reduce the environmental impact of the system comes from the use of heat pumps instead of gas boilers for heating, which reduces the GWP from approximately 37 to 13 g Co2 eq/m^2 yr. The addition of PV panels provides a significant contribution to reducing CO2 emissions, which reaches a minimum of 3.2 g Co2 eq/m^2 yr in Scenario 9. From then onward, the use of batteries has the opposite effect, because of the losses in the charge/discharge cycle and of the large GHG emissions connected to the battery production process.

Concerning other technologies installed, thermal energy storage is used in most scenarios. A relatively small thermal storage is installed in Scenarios 2–9; whereas in Scenarios 10–14 larger systems are installed, following the same principle as for the batteries.

Additional information related to the installation of PV panels is provided in Figure 13. These results start providing insights related to the main topic of this paper. For low installed PV capacity, panels are equipped on the flat and on the south-oriented roof. On the flat roof, the panels are positioned with a south orientation and with a 30°tilt, according to common practice. However, at even a small increase in the total installed PV capacity, the west-oriented roof is used over the east-oriented roof, and the azimuth and tilt of the panels installed on the flat roof changes. This is likely because west

Optimal Orientation and the Role of Self-Consumption at district scale

One additional objective of this study is to determine the effect of the interaction between the hourly variation of the thermal and electrical demand, the energy system, and the choice of the surface where the solar panels are installed.

The results shown in Figure 13 serve as an excellent starting point for this discussion. Although the south-facing rooftops are selected first, west-facing surfaces are chosen over east-facing surfaces. This was further explored in the case of a building with no tilted roofs: in this case, the optimizer has full freedom of choice in terms of orientation and tilt, rather than being forced to choose among a limited set of options, and can therefore provide more insight.

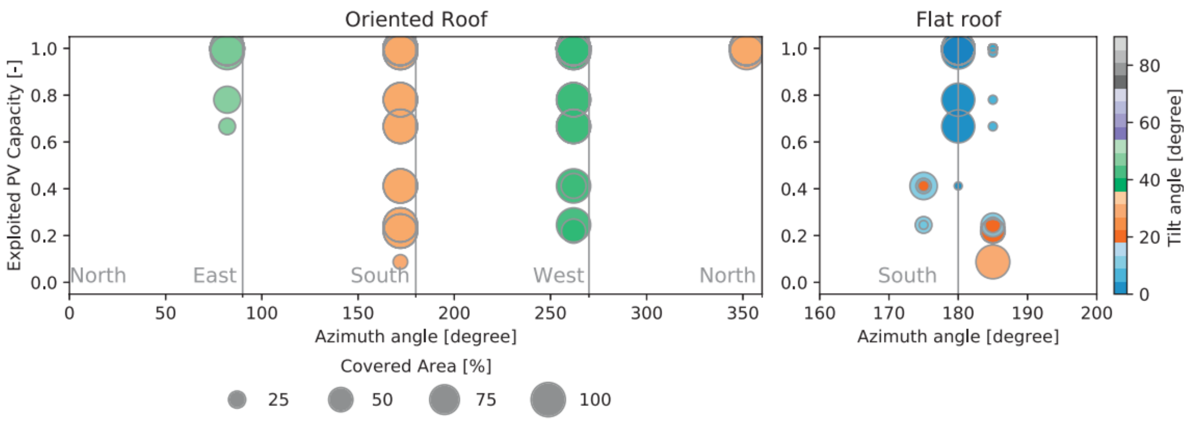


Figure 13: Optimal distribution of PV installation for different roofs.

These results are presented in Figure 14. Figure 14A refers to the reference pricing case of 0.24 CHF/kWh for electricity purchased from the grid and a feed-in tariffs of 0.08 CHF/kWh, whereas Figure 14B refers to the same case but with a 0 CHF/kWh feed-in price. As expected, given its highest yearly energy generation, south-oriented panels are preferred; however, at feed-in tariffs of 0 CHF/kWh, the panels are slightly oriented toward the west and have a higher tilt, especially in the cases with a lower total installed PV capacity.

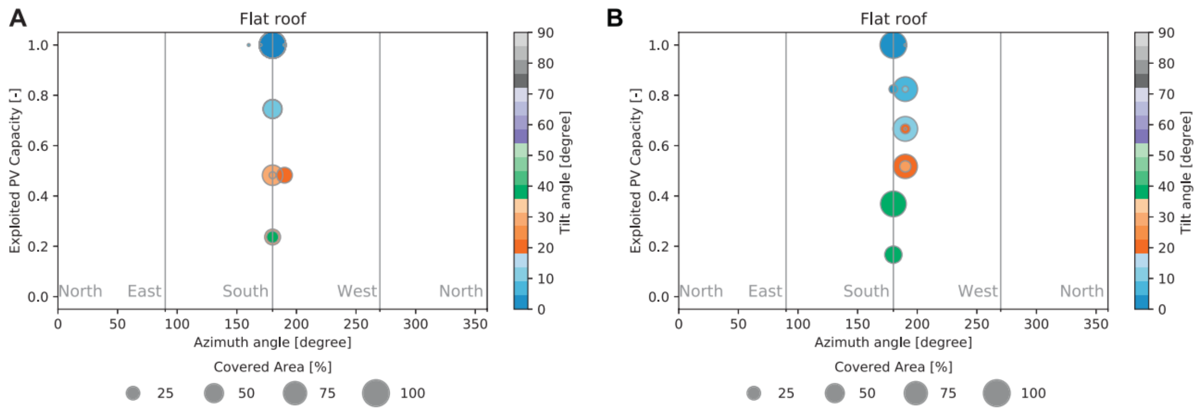


Figure 14: Optimal PV orientation for different installed capacities on a flat roof: (A) cost optimal placement for an electricity price of 0.24 CHF/kWh and feed-in tariffs of 0.08 CHF/kWh, and (B) optimal placement for self consumption for an electricity price of 0.24 CHF/kWh and feed-in tariffs of 0 CHF/kWh.

In most residential buildings, the main energy demand is in the evening, when people are at home, and during the heating season in winter, when the Sun is lower in the sky, thus explaining this orientation shift. However, this effect is minor, since the developed model includes optimal scheduling. This leads to the conclusion that, although this effect does not seem to have a substantial influence on the overall performance, the common practice of installing PV panels with the azimuth and tilt that maximizes energy generation may not be the best choice, especially when the objective is to maximize self-consumption. This trend is only seen for scenarios where only parts of the roofs are covered with PV panels: when the whole roof is covered, the optimizer prioritizes the maximization of the yearly generation, thus favoring azimuth and tilt angles that minimize shading among panels.

Comparison With Flat Roof Assumption

This work also aimed to provide an estimation of the error generated by assuming horizontal panels on the entire roof surface when attempting to estimate the PV potential from distributed generation. Although this assumption allows a simpler analysis and can rely on more limited set of information, it also introduces error.

The extent of the deviation between the "simplified" and "detailed" approaches for the 40 buildings with individual roofs and load profiles is shown in Figure 15A. For low exploited PV capacity, the general trend is that the best surfaces are used, and, whenever possible, the tilt angle is selected to maximize the yearly energy generation. As a result, the simplified assumption of panels installed with zero azimuth and tilt causes an underestimation of the generated electricity, and a consequent overestimation of the overall operational expenses. As “worse” roofs are used, the error is reduced, until the error sign reverses; for very high levels of PV penetration, as west-, east- and north-oriented roofs are exploited, the simplified flat panel assumption instead becomes an overestimation of the total capacity. While the error largely depends on the individual case, it generally ranges between −12 and +20% for the generated electricity, and −20% and +20% for the operational expenses.

Unlike the estimation of generated electricity, the error seen in the estimated operating expenses does not increase monotonically, but peaks at approximately 50% PV capacity. This can be explained by the difference in feed–in and electricity prices. The error in the estimation of the operational expenses is low in systems with low PV capacity. Here, SC is highest and can be maximized with the optimal scheduling of electrical loads. At some point, these scheduling measures are fully exploited in case of the simplified approach, all additional generated electricity is completely fed into the grid. In contrast, in the full approach “worse” roofs are used, which generate less electricity but lead to a better match of demand and supply profiles. Hence, it leads to further increase of self consumption, causing the peak of overestimating costs at 50% PV capacity. After this point, the limit of self consumption in the full approach is reached and the overproduction of electricity in the simplified approach is so high, that the revenues from the feed-in tariffs decrease the electricity bill drastically.

Whereas Figure 15A shows the behavior of “average” buildings, Figure 15B shows some outliers, i.e. buildings that behave remarkably differently from the rest. In the case of buildings with very high PV potential, the simplified approach tends to always underestimate the potential. Buildings with completely flat roofs are an example of this case: here, in almost all scenarios, the optimal placement involves using panels with a 30° tilt, which generates more energy than the flat case. On the other hand, when the PV potential of the building is very low, the electricity generated in the simplified approach is always overestimated; this can be the case of a house with a pitched roof facing east and west, where all available surfaces have a lower potential compared to a flat roof and, hence, the simplified approach tends to always overestimate the potential.

Impact on the Grid

The main rationale for not following the common practice of installing PV panels with azimuth and tilt that maximize yearly energy generation is related to the benefits that this gives toward maximizing SC. For a system connected to the grid, the maximizing SC helps to balance the grid and thus avoids excessive swings in the use of centralized power generation units. This aspect can become crucial once renewable energy sources (especially uncontrollable ones, such as wind and solar power) take up a significant share of the national energy mix.

Figure 16 allows getting a better understanding of this point, and of how it is connected to the matter of PV panels installation on top of roofs. Here, as demonstrated from the deviation between the energy generated by the optimal system (solid purple line) installed on a real roof and the energy generated by a hypothetical system with all panels oriented south with a 30°angle (dashed purple line), the error,

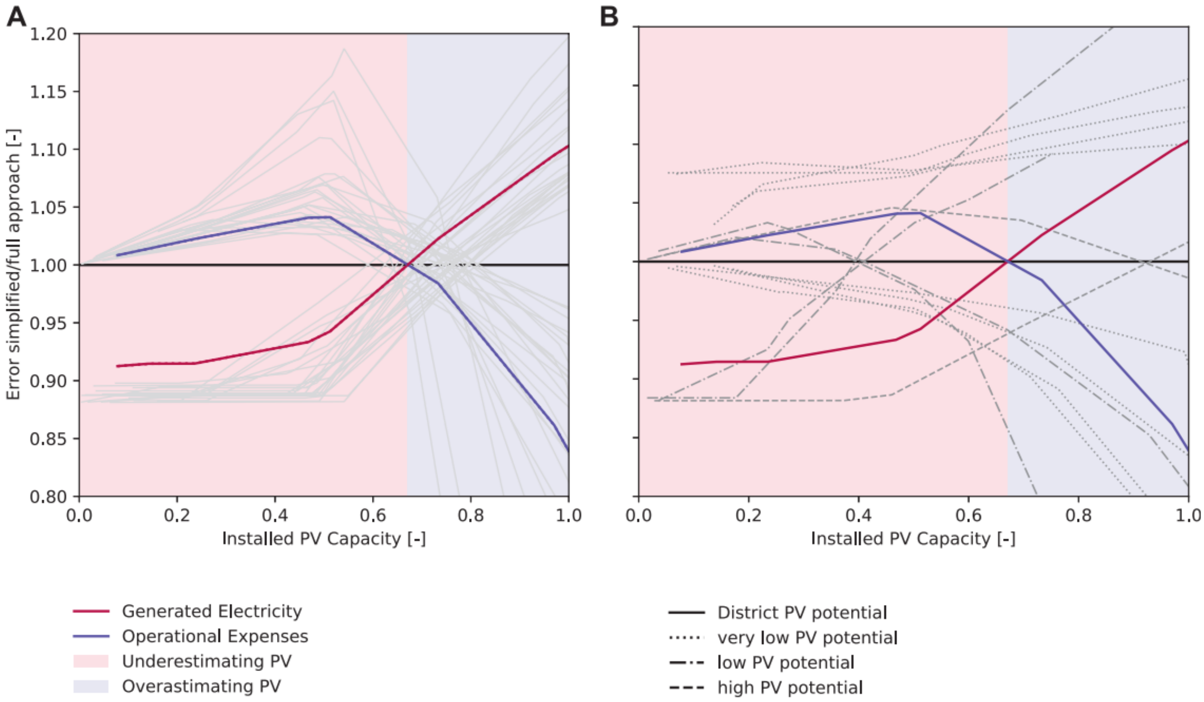


Figure 15: Error caused by assuming horizontal PV panels to optimal PV orientation for a district (colored lines) of 40 buildings (gray lines); Buildings with (A) average behavior (B) outlier behavior.

that is generated by not considering the orientation of the PV panels, is apparent. With a ratio of surface area of installed PV panels to the heated surface of just under 50%, the yearly demand of the building can be satisfied locally.

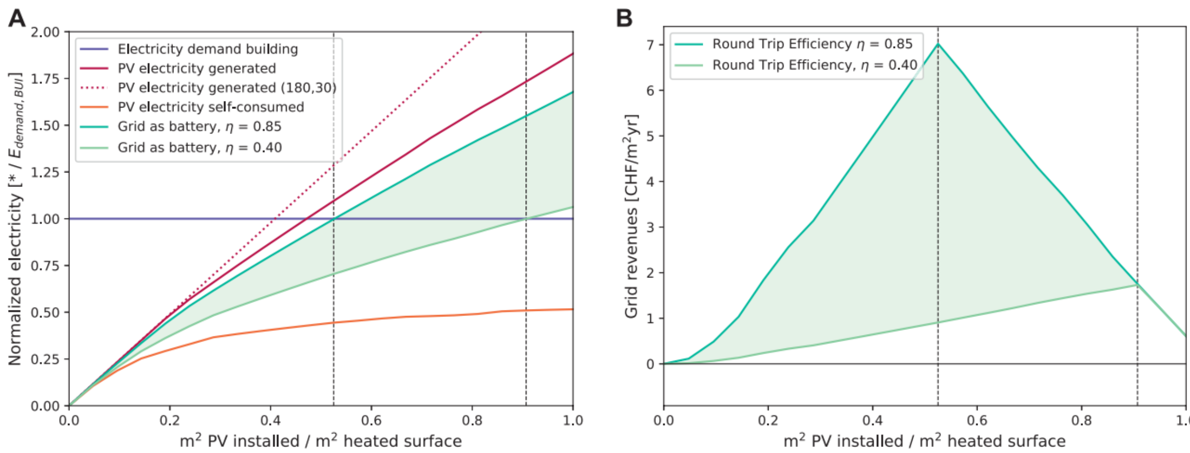


Figure 16: (A) The need of PV panels of a typical residential building in Switzerland to reach self-sufficiency with re-import. (B) Revenues as a function of installed PV capacity and grid efficiency from the perspective of the grid. The grid buys electricity at a feed-in tariffs of 0.08 CHF/kWh and resells for electricity price 0.24 CHF/kWh.

However, this perspective considers the grid as a perfect energy storage system. As shown by the actual value of the PV electricity that is self-consumed, most of the generated electricity is sold to the grid, and then purchased back when needed. The share of the demand that is satisfied with the energy generated from the PV panels increases with the PV surface installed; however, this share saturates at around 50% of the demand.

From the point of view of each individual prosumer, the grid can be seen as a battery that is able to absorb excess energy from distributed generation and sell it back when the demand exceeds the generation. There are several ways for the grid to fulfill this role: pumped hydroelectric storage is the most commonly used [39]: [40], whereas the use of large battery systems is still limited to few cases, and other technologies (such as compressed air storage or hydrogen) are yet to reach market maturity. Based on this an estimation of the PV system size required for a reference residence to achieve a net zero balance between energy locally generated and consumed for different values of the average efficiency of the storage is shown in Figure 16A. This assumption has a dramatic influence on the surface required for energy balance: for $\eta_{grid\text{-}as\text{-}storage}$=0.85 (which would be the case of lithium-ion batteries), the overall surface required would only slightly increase from the $\eta_{grid\text{-}as\text{-}storage}$=1 assumption. If, however, a much lower efficiency is assumed ($\eta_{grid\text{-}as\text{-}storage}$=0.40, which would be in the range of what can be expected when using hydrogen for energy storage), the surface of PV panels installed to reach self-sufficiency is almost doubled.

The effects of the efficiency of the grid as storage for the grid operators can be observed in Figure 16B, based on the assumption of 24/8 ct/kWh for electricity purchased from/sold to the grid. When ηgrid−as−storage is high, most of the energy purchased from the prosumers is able to be sold back, and hence the profit is large. With a lower ηgrid−as−storage, the profits decreases dramatically from the perspective of the grid.

The common interest in efficient grid infrastructure is revealed by Figure 16. From the perspective of the grid operator, profits can be higher as less energy is lost in the charge–discharge cycle, and these profits can be used to reinvest into upgrading the grid itself, generating a positive, cyclic effect. From the perspective of the building energy system, self-sufficiency can be achieved with a lower surface of PV panels installed (and, hence, with lower investment costs) and the supply is more secure, since there is 75% less traffic in the network.

The investigation of a different way to deal with the limitations of the grid is shown in Figure 17. One solution would be to increase the level of self-consumption. The effect of taking into account the effect of the grid-balance constraint on the installation decision of PV panels and on the preferred azimuth and tilt is shown in Figures 17A,B. Here, two alternative means from the perspective of the grid operator implemented to reduce the perturbations generated on the grid by individual prosumers: limiting the amplitude of power variations compared with an average value, or reducing ratio between the feed-in tariffs and electricity cost. Only one solution of the Pareto front is included here, i.e., that which minimizes the TOTEX.

The results of the first strategy are shown in Figure 17A. When no limitation is applied (left plot), almost all PV panels are installed facing south: with no limitation to the power exchanged with the grid, the

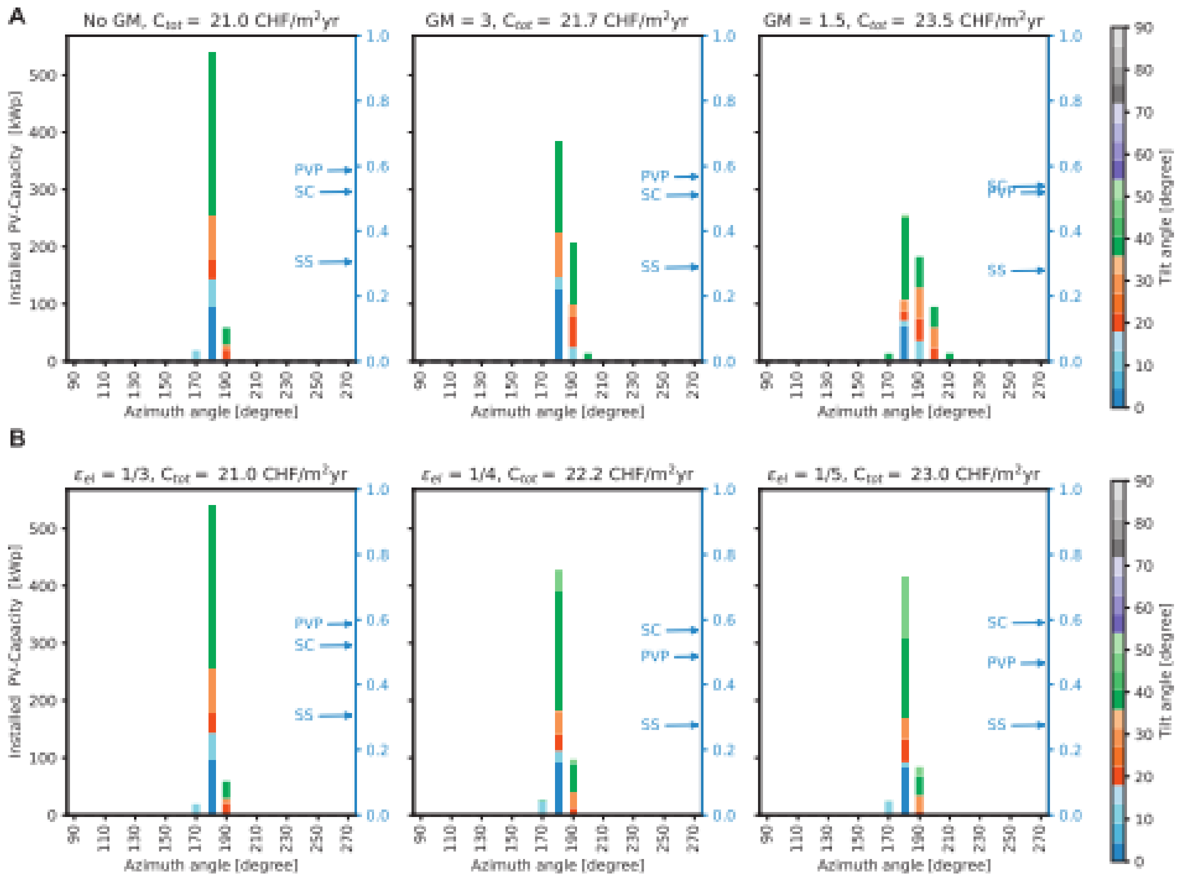


Figure 17: Distribution of PV installation and orientation for total cost optimization of 40 buildings with individual load profiles. Assumption of flat roof with unconstrained orientation possibilities. (A) Three different grid constraints. (B) Three different electricity price shares η_{el}=feed-in tariff/electricity price.

optimizer selects the configuration that maximizes energy generation. When a limited restriction is applied (GM = 3, center plot), there is a clear shift toward the west; even though the variation only referred to less then half of the installed PV capacity and for only 10°rotation,a clear trend is visible. This is confirmed when a stricter limitation on grid exchanges is imposed (GM = 1.5, right plot), where less than half of the panels are installed toward south and the average rotation toward the west is even higher. However, this has a relatively small effect on the SC, which only increases from 0.52 to 0.54.

The results of changing the relative price between energy purchased from and sold to the grid is shown in Figure 17B. The effect on the azimuth is less evident, but still present. However, a more distinct effect on the tilt angle is seen, which tends to increase (from 30° to 40°). Also, it appears that the effect on the SC is higher in this case (it increases from 0.52 to 0.59), which may be related to the fact that for electrified heating systems, the electricity demand is highest during winter, where the Sun is lower in the sky. Hence, by increasing the tilt angle, SC can be increased.

The analysis of a district with 40 buildings with individual roof orientation and demand profiles demonstrates that the best economic performance is achieved with around 40% rooftop occupancy, as shown in Figure 18. Even though the optimal orientation is impacted by the orientation of available surfaces, the previous trend of different policies can be confirmed in Figure 18A as well as in Figure 18B.

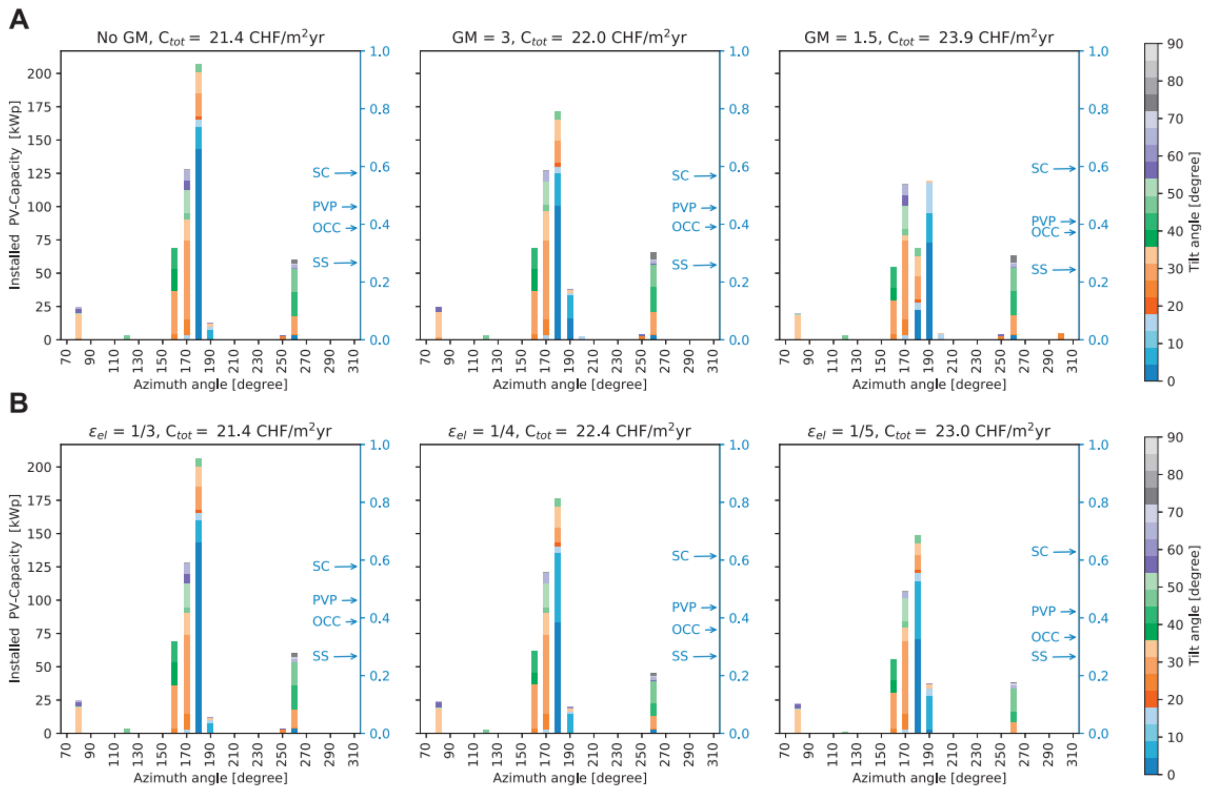


Figure 18: Distribution of PV installation and orientation for total cost optimization of 40 buildings with individual load profiles and real roof orientations. occupancy (OCC) (A) Three different Grid constraints. (B) Three different electricity price shares η_{el} feed-in tariff/electricity price.

6.3. Conclusion

The results confirm the validity of the common assumption of the favorability of south-oriented modules with an approximate tilt of 30°. However, this does not hold true when resources are available for more modules or when the focus shifts to clusters of buildings. To optimize (SC), the optimal orientation is further west and with higher tilt than the standard solution. To maximize the PV capacity on the roof, the use of horizontal panels maximizes the usable roof area.

The most interesting results, however, are related to the interaction with the grid. For higher levels of PV penetration, the role of the grid becomes crucial. Grid operators have the power to influence the quantity as well as the quality of grid exchange by acting in different directions:

- Grid efficiency: High grid efficiency is a common interest for both the building owner and the grid operator. With an 85% grid efficiency, a residential building would need around half of its heated surface in area of PV modules to be self sufficient. The point of SS also marks the maximum grid revenue at almost 7 CHF/m^2yr. A lower round–trip efficiency requires more PV panels to achieve SS, generates a greater stress on the grid, and reduces annual grid revenues.

- Feed-in: The pricing of the electricity exchange with the grid is influences the feed-in to the grid. For lower feed–in prices (or higher demand prices), the most economic solution is to increase tilt angles and slightly lower the PV penetration. This increases SC for a constant level of SS (Figure 17B).
- Peak power: Constraining the peak power of the grid exchange leads to a variation in azimuth angles. By moving panels 20°westward and optimally scheduling the operation, the peak can be reduced by 50% while total costs increase by 8.3%.

  Even though the optimal orientation strategy is impacted by the orientation of available surfaces, the trend of different grid policies is confirmed by analyzing a 40-building district with individual roof orientation and demand profiles. Comparing the resulting optimally oriented and horizontally oriented panels indicates that the latter generated high error in the estimation of the PV performance. Assuming horizontal panels, causes an overestimation in operating costs by approximately 5 and a 10% underestimation in generated electricity for low PV surfaces. For greater PV surfaces installed, the trend is reversed, and the relative error can increase to up to 20%.

7. Chapter 4: The future digitalization of smart grids

This chapter is drawn from the article of Lo Cascio, Girardin, Zhenjun and Maréchal, "How Smart is the Grid" [9].

In the past two years, the 90 % of the data in the world were created and 2.5 quintillion bytes of data are created every day [41]. This is thanks to the digital technologies that have also made expand the sectorial conceptual borders, especially for the smart grid archetype, where end-users and complementary sectors like transportation, tends to be intimately linked. This is also thanks to the advances in computing power and efficiency have enabled more powerful and sophisticated analytic, such as artificial intelligence and automation [42]. According to the International Energy Agency [43], 'digital technologies can help make the energy system more intelligent, reliable and sustainable, whereas it is also raising security and privacy risks, changing market.' However, if we put ourselves in a meta-perspective and, if we reframe this scenario, we might also convince that the market is changing the digitalization, making the energy system more connected for sure. But, intelligent? Resilient? Sustainable? The exuberant availability of electronic devices [44], for instance, seems to be the proof of the presence of an uncontrolled commercial speculative pool whose inertia, if not properly addressed, would likely affect the evolution of the smart grid, exchanging threats with strengths.

This chapter provides a general analysis of the technological framework and the emerging trends for the smart grid domain, that is:

- Internet of Things
- Smart meters

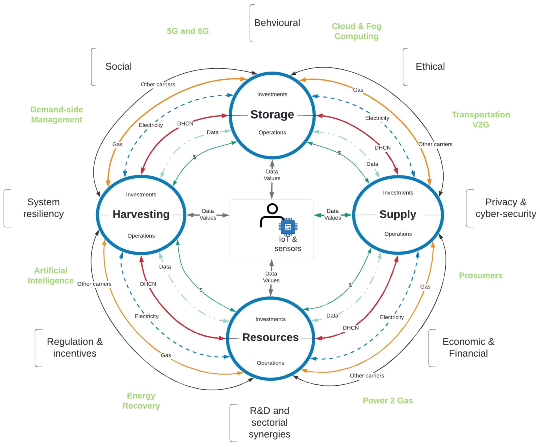


Figure 19: An idealization of smart grid universe.

- Blockchain
- 5G/6G
- Demand response & aggregators
- Cloud computing
- Communication protocols
- Prosumers
- Artificial intelligence
- Big Data & quantum computing
- Complementary applications, sectorial integration & synergies, technology

7.1. Internet of Things

The internet of Things IoT global market for end-users is expected to grow up to 1.6 trillion in US dollars by 2025 [45]. According to *Fortune Business Inside* [46] instead, the IoT market is expected to reach 1.1 trillion US dollars in 2026. In any case, the sophisticated e-cosmo is actually a multidomain connected, fast-interacting set of physical players (subjects and objects) and every measurable evolution, even its associable economic growth, will be certainly related by this existing sectorial interdependency. In this perspective, an example of technology-to-technology synergy could be represented by the so-called blockchain, which is likely to be a game-changer tool for peer-to-peer energy transactions while it will work as a catalyzer for the IoT market growth. But, the 'evolution equation' of the smart grid is constituted by further several variables that will determine the final picture of the digital era e.g. innovation in telecommunication, information technologies, regulation and as well as anthropological issues. In the following section, we propose an in-depth analysis of those further main archetypes involved.

7.2. Smart meters

Smart metering has the potential to revolutionize access to energy consumption data but, as highlighted by [47], a coordinated effort is needed between legislation, funding bodies and researchers to unlock its potential. From this perspective, the European Union issued Directives 2009/72/EC, 2009/73/EC, and Directive 2012/27/EC that insisted on making smart meters available to the majority of households in the EU by 2020. Italy was the first European country where smart meters rollout started at a large scale, followed by France who started the process in 2013, while in the UK and The Netherlands smart meters have been introduced simultaneously in gas and electricity sectors [48]. Of course, a rollout phase is a complex process, and operators have to deal with different aspects and issues ranging from logistic to complex aspects relative to the social domain, passing through financial and technical challenges. In this sense, the diffusion of a given technology is also intimately linked/bounded by the perception and awareness of people of the technology itself. For example, [49] investigated the awareness and acceptance level of smart meters among social media users in Poland. Findings suggested a low level of public awareness for this technology for this geographical context, thus limiting the potential benefits that smart meters could generate for them. However, smart meters offer the possibility to read in real time rates and pricing policies, allowing the implementation of demand response programs and demand side management programs. These features are being exploited by utilities in order to achieve energy efficiency, increasing network reliability and produce significant economic savings to the utility and the customer [50]. However, ”defining the environment for analyzing streamed big data in real time is not an easy task.” [51]. There are different approach to this problem and the most promising is the so called Lambda Architecture:a data-processing architecture capable to orchestrate ’big’ quantities of data by employing both batch and stream-processing methods.

7.3. Blockchain

”UNC Charlotte research team performed a comprehensive worldwide market survey and investigated more than 200 energy blockchain companies. When combined with smart contracts [52], blockchain is capable to enable a decentralized market [53]. This aspect opens the possibility to realize what has been defined by some scientists as the ‘energy democratization’ where market dynamics are induced by the community of end-users rather than a centralized organization (figure 3). [54], faced the design aspect of a local decentralized energy market based on blockchain technology. To this aim, the authors realized a proof-of-concept model, including a simulation of a local blockchain-based market where users can bilaterally exchange energy. However, it emerges that, even if they have successfully passed the proof-of-concept phase, most projects are still in the early development stage, and thus, further research efforts will have to demonstrate if the technology can reach its technical viability and commercial potential [55]

7.4. 5G/6G

if 5G will enable communication with unprecedented performance, on the other hand, 6G will drastically shape the communication framework, generating new societal paradigms, thus opening the way to new services such as holographic communication, high precision manufacturing, allowing artificial intelligence achieving its maximum potential [56]. From a smart city perspective instead, according to [57], with 5G technology energy systems and transportation networks are individually smart. The difference with 6G is that the control and optimization of energy and transport infrastructure will occur in a holistic and integrated fashion, thus, enabling a truly smart city. Furthermore, both drones and terrestrial stations may need connectivity to low orbit satellites and CubSat [58].

7.5. Demand response & aggregators

Today's ICT allows employing demand response energy management systems, whose scope is to control the energy demand to match the available energy resources without adding new generation capacity [59]. Today, demand response can be applied also to the residential sector. Here, the presence of highly connected home appliances i.e. IoTs will enable a performing communication that is fundamental for controlling and optimizing the energy system in a holistic and proactive fashion. Precisely, from this review study, it emerges the need for a highly efficient ICT infrastructure, which must be associated with IoT, in order to properly interact with end-users, for managing and balancing the energy production and demand.

7.6. Cloud computing

Cloud computing provides large-scale integrated processing capabilities which are more economically sustainable [60]. [61], discussed the role of cloud computing within the smart grid framework, identifying this technology as a potentially beneficial for power system optimization, mitigate disasters, increasing resilience to large-scale failure. If this last aspect is true from one side, from the other side, data centers have to deal with different categories of risks ranging from regulatory, technological, political to climate/natural. From the energy point of view, the cooling energy consumption can reach up to 45% of the total consumption of data centers in the case of inefficient cooling systems. As the increase in data processing requires increasingly power, innovative cooling solutions are emerging such as Direct-to-Chip or Liquid Immersive Cooling where servers and storage are fully immersed in dielectric fluid [62].

7.7. Communication protocols

Communication protocols refer to the set of rules that enable different entities of a communication system to share information through variations of physical quantities. The protocol comprises the rules, syntax, semantics and, synchronization of the communication [63]. In [64] discussed some of the major communication protocols such as *ZigBee* and *WiMAX*, with a specific focus on their application in smart grids and, as stated by the authors, "smart devices have started to reach the consumer market but the interoperability and complete solution for smart grid environment is still far away".

7.8. Prosumers

Prosumer refers to a player which is involved in the production and utilization of a generic good and it can be translated in “production by consumers”. A possible successful scenario for prosumers’ integration in the energy market could improve residential and commercial energy efficiency, democratize demand-response and prepare society for distributed clean energy technologies. However, the great market design is needed at different levels otherwise, it could easily undermine grid reliability, erode sensitive protections on privacy and inflate expectations to the degree that the prosumer revolution satisfies nobody [65].

7.9. Artificial intelligence

Artificial intelligence and machine learning are increasingly seen as key technologies for building more decentralized and resilient energy grids. from a technological perspective, as reported in [66], the artificial intelligence has made such huge steps forward that we have arrived at a scientific frontier where – citing the authors – ‘artificial intelligence needs new hardware, not just new algorithm’. The idea of the so-called neuromorphic computing is to design computer chips inspired to the brain, thus merging memory and processing units, achieving impressive computational power and speed with very little power consumption.

7.10. Big Data & quantum computing

Smart sensors networks are a great opportunity for smart grid applications due to the high level of magnitude of data gathering. However, it also brings new challenges and costs for storing and processing consistent flows of information with a high frequency [67], which are commonly identified with the term ‘big data’. For big data analysis, quantum computing may play a fundamental role. In fact, [68] observed that quantum-mechanical systems have an information-processing capability much greater than that of corresponding classical systems, and could thus potentially be used to implement a new type of powerful computer’ [69]. In fact, concerning the smart grid context, some proofs-of-concept have been already provided to solve simplified problems, ranging from traffic flow optimization to route optimization for multimodal transport systems [70]. Furthermore, quantum computing is truly a game-changing technology since, as previously stated, it will also likely push the boundaries of cyber security and cryptography. Finally, in a smart grid perspective, quantum computing will enable new paradigms in the energy market by effectively preserving users’ privacy and their economic transactions.

7.11. Sectorial integration & synergies

In addition to the abovementioned paradigms and technologies, there is plenty of further innovative energy applications, management strategies and emerging solutions that, in some form and in some way, will characterize the portrait of the smart grid of the future. For example, without the aim of exhaustiveness, vehicles-to-grid (V2G) and battery swapping applications [71] are complementary paradigms that will take part in the smart grid shaping process for some contexts. Similarly, 5th generation CO2 district heating network and power-to-gas applications [72] are another issues that scientists are currently dealing with. Also, energy storage, in a broader sense of the term, and sectorial integration i.e. industrial symbiosis, waste heat recovery, is to increase the flexibility and sustainability of energy systems operations, affecting decisively, the evolution of our technological landscape for the energy context. Finally, some minor applications such as energy recovery from natural gas distribution [73] and emerging control strategies such as gas-bagging [74] applications, in a long term perspective are likely to contribute to shaping the smart grid scenario as well. Or, for the sake of ontological coherency, the smart grid scenario, intended as a whole, is likely to shape the contribution of these applications. Besides, the smart grid of the future will be likely characterized by frontier technologies that are currently being studied or developed. For instance, researchers are developing a technology to convert a wall into a trackpad and motion sensor and this could be achieved thanks to a conductive paint [75]. Once this technology will reach a certain level of matureness, smart walls will be presumably able to track people's gestures or monitor appliances. As regards this aspect, it comes intuitively to understand the potential level of insights that could be achieved by monitoring people's body language, gestures and so on. Further aspects affecting the smart grid of the future could reside in complementary sectors and their technological advances. For instance, the space exploration and colonization sector have synergies with the smart grid sector. In fact, "NASA and smart grid both need autonomous controls" [76]. A further practical example of intersectoral synergy can be represented by the *SpaceX Starlink* project. This consists of a constellation of thousands of mass-produced small satellites working in combination with ground transceivers, to provide broad internet access, thus improving smart grid applications performance, making it easy to implement smart grid technologies also in remote areas.

8. Conclusions

The foreseen important increase of the penetration of distributed renewable energies technologies into the electricity distribution grid is expected to lead to strategic challenges, especially in Switzerland where the renewable content of the grid energy mix is actually high

In this report, best investment strategies have been proposed following four different approaches:

- selection of a reduced set of indicators to manage the energy transition and elaborate relevant communication on the strategic investment decisions;
- development of decentralized multi-energy infrastructure leveraging on the presence of on-site big energy prosumers;
- optimisation of the energy flows at district scale with a grid-aware perspective. This typically include coordinated investement in layout of photovoltaic pannels in roofs and fassade of energy autonomous districts;
- investment in the digitalisation of smart grid. This include, for example, the development of energy-backed cryptocurrencies and smart-contract technologies to boost the energy transition with new decentralized energy markets.

The results of this work have been published in open-access journals and presented to the industrial partners to support the elaboration of management and planning strategies for the energy transition of urban energy systems.

References

[1] Paul Stadler, Luc Girardin, Araz Ashouri, and François Maréchal. Contribution of model predictive control in the integration of renewable energy sources within the built environment. *Frontiers in Energy Research*, 6:22, 2018.

[2] Paul Michael Stadler. *Model-based sizing of building energy systems with renewable sources*. PhD thesis, EPFL, Lausanne, 2019.

[3] Raluca Suciu, Luc Girardin, and François Maréchal. Energy integration of co2 networks and power to gas for emerging energy autonomous cities in europe. *Energy*, 157:830–842, 2018.

[4] Raluca Suciu, Paul Stadler, Ivan Kantor, Luc Girardin, and Francois Marechal. Systematic integration of energy-optimal buildings with district networks. *Energies*, 12(15):2945, 2019.

[5] Luise Middelhauve, Lionel Bloch, Jordan Holweger, Paul Michael Stadler, and Luc Girardin. 5d2 - detailed evaluation of the grid operation bottlenecks and load shifting potential for the ref-erence system - deliverable 1.2.2. Technical report, EPFL Valais/Neuchâtel, 2019.

[6] Luise Middelhauve, Alessio Santecchia, Luc Girardin, François Maréchal, and Manuele Margni. Key performance indicators for decision making in building energy systems. *Proceedings of ECOS 2020*, pages 388–400, 2020.

[7] Bastien Bornand, Luc Girardin, Francesca Belfiore, Jean-Loup Robineau, Stéphane Bottallo, and François Maréchal. Investment planning methodology for complex urban energy systems applied to a hospital site. *Frontiers in Energy Research*, 8:264, 2020.

[8] Luise Middelhauve, Francesco Baldi, Paul Stadler, and François Maréchal. Grid-aware layout of photovoltaic panels in sustainable building energy systems. *Frontiers in Energy Research*, 8:317, 2021.

[9] Ermanno Lo Cascio, Luc Girardin, Zhenjun Ma, and François Maréchal. How smart is the grid? *Frontiers in Energy Research*, 2021 - In review.

[10] SIA. 2024:2015 Raumnutzungsdaten für die Energie- und Gebäudetechnik. *Schweizerischer Ingenieur und Architektenverein*, 2015.

[11] Luc Girardin. *A GIS-based Methodology for the Evaluation of Integrated Energy Systems in Urban Area*. PhD thesis, EPFL, 2012.

[12] Dimitrios-Sotirios Kourkoumpas, Georgios Benekos, Nikolaos Nikolopoulos, Sotirios Karellas, Panagiotis Grammelis, and Emmanouel Kakaras. A review of key environmental and energy performance indicators for the case of renewable energy systems when integrated with storage solutions. *Applied Energy*, 231:380–398, December 2018.

[13] Oswaldo Lucon and et. al. Buildings. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, United Kingdom and New York, 2014.

[14] Kantor Ivan and Alessio Santecchia. D5.7 – Report on LC assessment tools based on the results of MORE and EPOS. *Coordinated Production For Better Resource Efficiency*, May 2019.

[15] Gregor Wernet, Christian Bauer, Bernhard Steubing, Jürgen Reinhard, Emilia Moreno-Ruiz, and Bo Weidema. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, 21(9):1218–1230, September 2016.

[16] Raphael Wu, Georgios Mavromatidis, Kristina Orehounig, and Jan Carmeliet. Multiobjective optimisation of energy systems and building envelope retrofit in a residential community. *Applied Energy*, 190:634–649, March 2017.

[17] Richard Turton, editor. *Analysis, synthesis, and design of chemical processes*. Prentice Hall, Upper Saddle River, NJ, 4th ed edition, 2012.

[18] Yuling Fan and Xiaohua Xia. A multi-objective optimization model for energy-efficiency building envelope retrofitting plan with rooftop PV system installation and maintenance. *Applied Energy*, 189:327–335, March 2017.

[19] Jordan Holweger, Lionel Bloch, Christophe Ballif, and Nicolas Wyrsch. Mitigating the impact of distributed PV in a low-voltage grid using electricity tariffs. *arXiv:1910.09807 [cs, eess]*, October 2019. arXiv: 1910.09807.

[20] Michael Hartner and al. et. Optimal sizing of residential PV-systems from a household and social cost perspective. *Solar Energy*, 141:49–58, January 2017.

[21] K. Branker, M.J.M. Pathak, and J.M. Pearce. A review of solar photovoltaic levelized cost of electricity. *Renewable and Sustainable Energy Reviews*, 15(9):4470–4482, December 2011.

[22] Lucien Borel and Daniel Favrat. *Thermodynamics and energy systems analysis. Vol. 1: From energy to exergy*. Engineering sciences Mechanical engineering. EPFL Press, Lausanne, 1. ed edition, 2010. OCLC: 845717782.

[23] D. Favrat, F. Marechal, and O. Epelly. The challenge of introducing an exergy indicator in a local law on energy. *Energy*, 33(2):130–136, February 2008.

[24] Rasmus Luthander, Joakim Widén, Daniel Nilsson, and Jenny Palm. Photovoltaic self-consumption in buildings: A review. *Applied Energy*, 142:80–94, March 2015.

[25] A. J. McEvoy, T. Markvart, and Luis Castañer, editors. *Practical handbook of photovoltaics: fundamentals and applications*. Academic Press, Waltham, MA, 2nd ed edition, 2012. OCLC: ocn714729581.

[26] Roozbeh Sangi and Dirk Müller. Exergy-based approaches for performance evaluation of building energy systems. *Sustainable Cities and Society*, 25:25–32, August 2016.

[27] ASTM International. *ASTM E917-17 - Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems*. ASTM International, West Conshohocken, PA, 2017.

[28] ASHRAE. *2003 ASHRAE Handbook: Heating, Ventilating, and Air-conditioning Applications*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2003.

[29] Tao Wang, Xiaodong Li, Pin-Chao Liao, and Dongping Fang. Building energy efficiency for public hospitals and healthcare facilities in china: Barriers and drivers. *Energy*, 103:588–597, 2016.

[30] Pablo Garcia-Herreros, Lei Zhang, Pratik Misra, Erdem Arslan, Sanjay Mehta, and Ignacio E Grossmann. Mixed-integer bilevel optimization for capacity planning with rational markets. *Computers & Chemical Engineering*, 86:33–47, 2016.

[31] Kaveh Khalili-Damghani, Madjid Tavana, and Soheil Sadi-Nezhad. An integrated multi-objective framework for solving multi-period project selection problems. *Applied Mathematics and Computation*, 219(6):3122 – 3138, 2012.

[32] Hür Ebuzer Bütün, Ivan Daniel Kantor, and François Maréchal. An Optimisation Approach for Long-Term Industrial Investment Planning. *Energies*, 12(21):4076, 2019.

[33] Hür Ebuzer Bütün. *Optimal retrofit and investment planning methodologies for improving industrial energy and resource efficiency*. EPFL, Lausanne, 2020.

[34] Bastien Maxence Bornand. *Integrated energy planning assistance for major consumers - Application : HUG – Cluse Roseraie Hospital district*. IPESE-EPFL, Lausanne, 2017. Master's Thesis.

[35] Andrea Franco, Marjan Shaker, Dikolela Kalubi, and Silvia Hostettler. A review of sustainable energy access and technologies for healthcare facilities in the global south. *Sustainable Energy Technologies and Assessments*, 22:92–105, 2017.

[36] Nils Christian Schüler. *Computational methods for multi-criteria decision support in urban planning*. PhD thesis, EPFL, Lausanne, 2018.

[37] Samira Fazlollahi, Stephane Laurent Bungener, Pierre Mandel, Gwenaelle Becker, and François Maréchal. Multi-objectives, multi-period optimization of district energy systems: I. selection of typical operating periods. *Computers and Chemical Engineering*, 65:13. 54–66, 2014.

[38] Suncalc sun position- und sun phases calculator. www.suncalc.org. Accessed: 2021-15-01.

[39] D.O. Akinyele and R.K. Rayudu. Review of energy storage technologies for sustainable power networks. *Sustainable Energy Technologies and Assessments*, 8:74–91, 2014.

[40] Turgut M. Gür. Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. *Energy Environ. Sci.*, 11:2696–2767, 2018.

[41] Bernard Marr. How Much Data Do We Create Every Day? The Mind-Blowing Stats Everyone Should Read. https://www.forbes.com/sites/bernardmarr/2018/05/21/how-much-data-do-we-create-every-day-the-mind-blowing-stats-everyone-should-read/#23336edf60ba, 2018. Online; accessed 23 March 2020.

[42] IEA. Digitalization & Energy. https://www.iea.org/reports/digitalisation-and-energy, 2017. Online; accessed 23 March 2020.

[43] IEA. Tracking energy integration. https://www.iea.org/reports/tracking-energy-integration-2020/smart-grids, 2020. Online; accessed 02 December 2020.

[44] Benjamin K Sovacool and Dylan D Furszyfer Del Rio. Smart home technologies in europe: A critical review of concepts, benefits, risks and policies. *Renewable and Sustainable Energy Reviews*, 120:109663, 2020.

[45] Statista. Forecast end-user spending on iot solutions worldwide from 2017 to 2025. https://www.statista.com/statistics/976313/global-iot-market-size/#statisticContaine, 2020. Online; accessed 23 January 2020.

[46] Fortune Business Insights. Iot Market Investment. https://www.fortunebusinessinsights.com/industry-reports/internet-of-things-iot-market-100307, 2020. Online; accessed 23 March 2020.

[47] Ellen Webborn and Tadj Oreszczyn. Champion the energy data revolution. *Nature Energy*, 4(8):624–626, 2019.

[48] Smart Energy International. Over 60 million households in Europe will have smart gas meters by 2022. https://www.smart-energy.com/magazine-article/smart-gas-meters-2022-eu/, 2017. Online; accessed 23 March 2020.

[49] Yash Chawla and Anna Kowalska-Pyzalska. Public awareness and consumer acceptance of smart meters among polish social media users. *Energies*, 12(14):2759, 2019.

[50] Luis I Minchala-Avila, Jairo Armijos, Daniel Pesántez, and Youmin Zhang. Design and implementation of a smart meter with demand response capabilities. *Energy Procedia*, 103:195–200, 2016.

[51] Zirije Hasani, Margita Kon-Popovska, and Goran Velinov. Lambda architecture for real time big data analytic. *ICT Innovations*, pages 133–143, 2014.

[52] Zibin Zheng, Shaoan Xie, Hong-Ning Dai, Xiangping Chen, and Huaimin Wang. Blockchain challenges and opportunities: A survey. *International Journal of Web and Grid Services*, 14(4):352–375, 2018.

[53] Yong Yuan and Fei-Yue Wang. Towards blockchain-based intelligent transportation systems. In *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*, pages 2663–2668. IEEE, 2016.

[54] Esther Mengelkamp, Benedikt Notheisen, Carolin Beer, David Dauer, and Christof Weinhardt. A blockchain-based smart grid: towards sustainable local energy markets. *Computer Science-Research and Development*, 33(1-2):207–214, 2018.

[55] Merlinda Andoni, Valentin Robu, David Flynn, Simone Abram, Dale Geach, David Jenkins, Peter McCallum, and Andrew Peacock. Blockchain technology in the energy sector: A systematic review of challenges and opportunities. *Renewable and Sustainable Energy Reviews*, 100:143–174, 2019.

[56] Emilio Calvanese Strinati, Sergio Barbarossa, José Luis Gonzalez-Jimenez, Dimitri Kténas, Nicolas Cassiau, and Cédric Dehos. 6g: The next frontier. *arXiv preprint arXiv:1901.03239*, 2019.

[57] Faisal Tariq, Muhammad Khandaker, Kai-Kit Wong, Muhammad Imran, Mehdi Bennis, and Merouane Debbah. A speculative study on 6g. *arXiv preprint arXiv:1902.06700*, 2019.

[58] NASA CubeSat Launch Initiativel. CubeSat 101 - Basic Concepts and Processes for First-Time CubeSat Developers. https://www.nasa.gov/sites/default/files/atoms/files/nasa_csli_cubesat_101_508.pdf, 2017. Online; accessed 23 March 2020.

[59] Haider Tarish Haider, Ong Hang See, and Wilfried Elmenreich. A review of residential demand response of smart grid. *Renewable and Sustainable Energy Reviews*, 59:166–178, 2016.

[60] Gerg O'Connor, Appzero. Gigaom - Moore's law gives way to Bezos's law. https://gigaom.com/2014/04/19/moores-law-gives-way-to-bezoss-law/, 2014. Online; accessed 23 March 2020.

[61] Baling Fang, Xiang Yin, Yi Tan, Canbing Li, Yunpeng Gao, Yijia Cao, and Jianliang Li. The contributions of cloud technologies to smart grid. *Renewable and Sustainable Energy Reviews*, 59:1326–1331, 2016.

[62] S. Campbell. Is Liquid Cooling Ready to Go Mainstream? https://www.hpcwire.com/2017/02/13/liquid-cooling-ready-go-mainstream/, 2017. Online; accessed 27 Nov 2020.

[63] Chris J Myers. *Asynchronous circuit design*. John Wiley & Sons, 2001.

[64] Ahmad Usman and Sajjad Haider Shami. Evolution of communication technologies for smart grid applications. *Renewable and Sustainable Energy Reviews*, 19:191–199, 2013.

[65] Yael Parag and Benjamin K Sovacool. Electricity market design for the prosumer era. *Nature energy*, 1(4):1–6, 2016.

[66] Dmitri Strukov, Giacomo Indiveri, Julie Grollier, and Stefano Fusi. Building brain-inspired computing. *Nature Communications*, 10(1), 2019.

[67] Manar Jaradat, Moath Jarrah, Abdelkader Bousselham, Yaser Jararweh, and Mahmoud Al-Ayyoub. The internet of energy: Smart sensor networks and big data management for smart grid. *Procedia Computer Science*, 56:592 – 597, 2015. The 10th International Conference on Future Networks and

Communications (FNC 2015) / The 12th International Conference on Mobile Systems and Pervasive Computing (MobiSPC 2015) Affiliated Workshops.

[68] Richard P Feynman. Simulating physics with computers. *Int. J. Theor. Phys*, 21(6/7), 1999.

[69] Jonathan A Jones, Michele Mosca, and Rasmus H Hansen. Implementation of a quantum search algorithm on a quantum computer. *Nature*, 393(6683):344–346, 1998.

[70] D-Wave, The Quantum Computing Company. Applications. https://www.dwavesys.com/applications, 2020. Online; accessed 23 March 2020.

[71] Willett Kempton and Jasna Tomić. Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. *Journal of power sources*, 144(1):268–279, 2005.

[72] Manuel Götz, Jonathan Lefebvre, Friedemann Mörs, Amy McDaniel Koch, Frank Graf, Siegfried Bajohr, Rainer Reimert, and Thomas Kolb. Renewable power-to-gas: A technological and economic review. *Renewable energy*, 85:1371–1390, 2016.

[73] Ermanno Lo Cascio, Marc Puig Von Friesen, and Corrado Schenone. Optimal retrofitting of natural gas pressure reduction stations for energy recovery. *Energy*, 153:387–399, 2018.

[74] Ermanno Lo Cascio, Bart De Schutter, and Corrado Schenone. Flexible energy harvesting from natural gas distribution networks through line-bagging. *Applied energy*, 229:253–263, 2018.

[75] Prachi Patel. How to Convert Your Wall into a Giant Touch Screen. https://www.scientificamerican.com/article/how-to-convert-your-wall-into-a-giant-touch-screen//, 2018. Online; accessed 23 March 2020.

[76] James F. Soeder. Smart Grid Development Issues for Terrestrial and Space Applications. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150002095.pdf, 2015. Online; accessed 23 March 2020.