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DisCREET

Distributed Cogeneration supporting Renewable Energy sources for the Electrification of Transport

Cost-efficient Decarbonization Pathways in the Swiss Residential Sector via Optimization of Design and Operation of Multi-Energy Systems including Mobility

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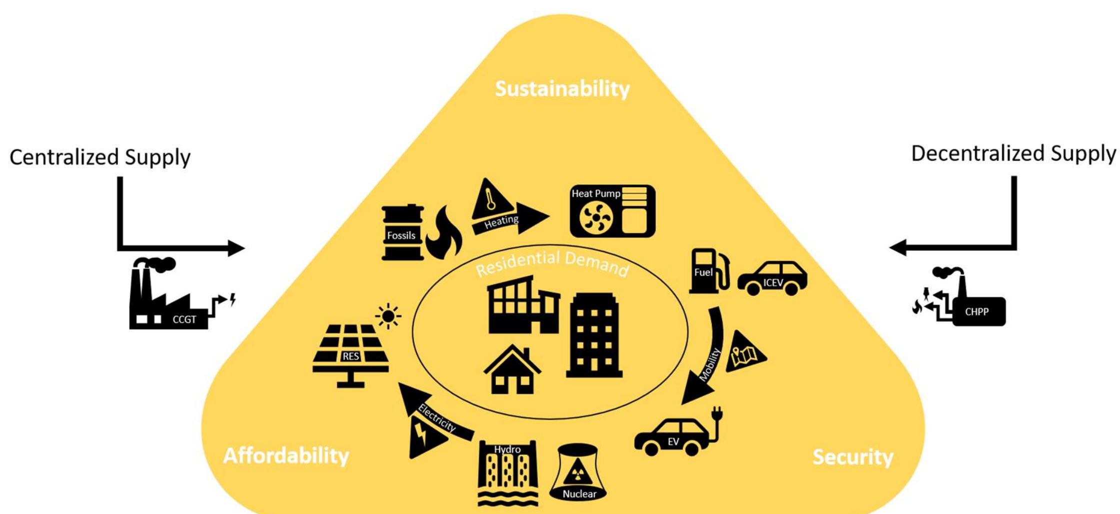

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Summary

Switzerland must quickly and drastically reduce its energy- and mobility-related greenhouse gas (GHG) emissions. In the energy- and emission-intensive residential sector, supply-side energy and mobility asset upgrades offer large opportunities for GHG emission mitigation. Particularly, the electrification of traditionally fossil fuel based heating and private mobility is expected to significantly reduce GHG emissions.

In order to promote this energy and mobility system transformation towards lower GHG emission levels while maintaining affordable energy prices and guaranteeing reliable energy supply, the DisCREET projects investigated how decentralized gas-based co-generation, can interact with increasing shares of partly intermittent renewable energy technologies (RET), energy storage systems (ESS) and other energy supply assets to optimally supply load sites with the required energy to power the residential electrification.

To efficiently address this complex field of interrelated, sector-coupled objectives under various techno-economic restrictions, the DisCREET project first and foremost developed a software tool based on the Energy Hub concept, which intends to guide and improve decision-making with regards to optimal energy system planning by numerically describing the relevant investment and operation decisions related to technological system upgrades.

The associated optimizations are carried out from the bottom-up perspective of well-informed residential consumers, which plan to upgrade their stationary energy assets and private vehicles based on strategic investment decisions, which take total system costs and lifecycle GHG emissions as the primal performance indicators to evaluate those decisions. These decisions, which define the optimal selection of technologies from a given portfolio, their optimal installation capacities, and their optimal operational schedules, are then useful for the consumers themselves, but also other stakeholders looking to understand the consequences of optimal consumer-based decision-making towards affordable, sustainable, and secure provision of the formers' thermal, electrical, and mobility-related energy demands.

These consequences of local decision-making are far-reaching. Results show that electrification of the residential and mobility sector can substantially reduce its GHG (up to -70% in best case scenarios), while offering comparable (and even slightly reduced) levels of total cost via the introduction of modern centralized and decentralized supply technologies. In this regard, local heat pumps, electric cars, and decentralized photovoltaic systems are the core technologies used to enable residential decarbonization. As a result of their installation the demand for electricity from the centralized energy grids shifts from unidirectional, uniform, and moderate levels of electricity demand, to bi-directional, strongly seasonal and intermittent as well as generally increased electricity demand levels, which would overburden the current centralized electricity supply system manifold, particularly in winter, if all consumers electrified their heating and mobility systems.

Under the consideration of limited electricity availability from the centralized electricity grid in Switzerland, local electrification must find ways to provide the additional electricity demands. Since also the space for roof-top PV installation is limited and this technology provides electricity mostly in summer, decentralized combined heat and power plants (CHPPs), operating on natural gas or biogas, can offer attractive solutions in such circumstances to ensure electricity supply. CHPPs are hence found particularly attractive, whenever its main competitor, the centralized electrical grid, is (partially) unavailable, exhibits a high carbon-content or is costly. Further, biogas-operated CHPPs are shown to significantly undercut GHG emission levels from centralized combined cycles gas turbines at acceptable total costs, when operating in conjunction with the mentioned core decentralized energy technologies.

Without consideration of the limitedness of the existing centralized energy systems, CHPPs are however mainly only attractive for cost-driven energy systems, for large demand sites, and at high heating supply temperatures.

Overall, the data, the methodology, the computational model, and the results presented in work enable robust suggestions for quick, affordable, secure, and deep decarbonization of the residential energy and mobility sector via electrification.

Take-home messages

- The presented, newly developed simulation tool based on the energy hub concept was found to be a solid and expandable way to holistically assess the joint electrification's benefits and culprits of the investigated multi-energy systems and vehicles based on total annualized cost, total lifecycle emissions under consideration of multiple systemic constraints and techno-economic conditions by optimally designing and operating heavily interlinked energy and mobility assets.
- Quick and deep electrification of the GHG emission- and energy-intense heating and mobility sectors is a feasible, vital, robust, and negative-cost path for the decarbonization of the Swiss residential demand sector allowing for GHG emission reduction of up to 70% at no additional cost and should thus be accelerated strongly and as soon as possible using readily available technologies, like photovoltaics, heat pumps, electric vehicles, and biogenic co-generation plants.
- Under the realization of seasonally limited and potentially decreasing existing, clean electricity supply from centralized hydro and nuclear power, residential electrification proves more challenging than under unlimited electricity supply. Nevertheless, decentralized energy hubs can still beneficially electrify the heating and mobility sectors in Switzerland (reducing total emissions by approximately 50% at no additional cost) by using a wide range of new centralized and decentralized assets, including biogenic co-generation plants utilized to supply on-demand, baseload electricity to the demand sites in winter, in conjunction with the existing electrical grid.
- The identified optimal solutions however are complex, multi-asset, multi-energy solutions that also bring drawbacks in need of further attention from researchers and stakeholders, like potentially prohibitive investment cost and increased share of embodied emissions, high seasonality and intermittency as well as bidirectionality of electrical supply, and a shift away from natural gas demand to lower yet hefty biogas demands, which all challenge upstream energy suppliers and their business models.

Zusammenfassung

Die Schweiz muss ihre energie- und mobilitätsbedingten Treibhausgasemissionen (THG) schnell und drastisch reduzieren. Im energie- und emissionsintensiven Wohnsektor bieten angebotsseitige Aufrüstungen von Energieanlagen und privaten Fahrzeugen große Potenziale zur Minderung der Treibhausgasemissionen. Insbesondere durch die Elektrifizierung von traditionell weitgehend fossil betriebenen Heizungsanlagen und privaten Fahrzeugen wird eine deutliche Reduzierung der Treibhausgasemissionen erwartet.

Um diese Transformation des Energie- und Mobilitätssystems hin zu geringeren Treibhausgasemissionen bei gleichzeitig erschwinglichen Energiepreisen und einer zuverlässigen Energieversorgung zu ermöglichen, untersuchte das DisCREET-Projekt, wie dezentrale gasbasierte Kraft-Wärme-Kopplungsanlagen (WKK-Anlagen) mit steigenden Anteilen intermittierender, erneuerbarer Stromerzeuger sowie Energiespeichersystemen und andere Energieversorgungsanlagen interagieren können, um Laststandorte optimal mit der erforderlichen Energie für die Elektrifizierung des Wohnsektors zu versorgen.

Zur effizienten und zielführenden Adressierung dieser komplexen Aufgabe miteinander verflochtene, sektorengekoppelte und techno-ökonomisch eingeschränkte Entscheidungen treffen zu können, hat DisCREET in erster Linie ein Software-Tool auf Basis des Energy Hub-Konzepts entwickelt. Dieses vereinfacht die optimale Energiesystemplanung durch die numerische Beschreibung der relevanten Investitions- und Betriebsentscheide möglicher Technologieaufrüstungen.

Die damit verbundenen Optimierungen erfolgen aus der Sicht gut informierter privater Verbraucher, die eine Modernisierung ihrer stationären Energieanlagen und privaten Fahrzeuge anhand der erwarteten Gesamtsystemkosten und Lebenszyklus-THG-Emissionen planen. Die verwandten Entscheide, welche die optimale Auswahl von Technologien aus vorgegebenen Technologieportfolios, ihre optimale Installationskapazitäten und ihre optimalen Betriebspläne umfassen, sind dann für die Verbraucher selbst aber auch für andere Interessengruppen, welche die Konsequenzen der optimalen verbraucherseitigen Entscheide für eine bezahlbare, nachhaltige und sichere Bereitstellung des thermischen, elektrischen und mobilitätsbezogenen Energiebedarfs verstehen möchten, nützlich.

Die Folgen dieser lokalen Entscheidungsfindung sind weitreichend. Die Ergebnisse zeigen, dass die Elektrifizierung des privaten Wohn- und Mobilitätssektors dessen THG erheblich reduzieren kann (im besten Fall bis zu -70%) und gleichzeitig vergleichbare (und teils sogar leicht reduzierte) Gesamtkosten durch die Einführung moderner zentraler und dezentraler Versorgungstechnologien bietet. Lokale Wärmepumpen, Elektroautos und dezentrale Photovoltaikanlagen sind dabei die Kerntechnologien, welche zur Dekarbonisierung von Wohngebäuden eingesetzt werden. Durch ihre Installation verschiebt sich die Stromnachfrage aus den zentralen Energienetzen von einer unidirektionalen, gleichmäßigen und moderaten Stromnachfrage hin zu einer bidirektionalen, stark saisonalen und intermittierenden sowie allgemein erhöhten Stromnachfrage, welche das derzeitige zentrale Stromversorgungssystems vor allem im Winter stark überlasten würden.

Unter Berücksichtigung der begrenzten Stromverfügbarkeit aus dem zentralen Stromnetz muss die lokale Elektrifizierung also Wege finden, den zusätzlichen Strombedarf von Elektroautos und Wärmepumpen zu decken. Da auch der Platz für PV-Aufdachanlagen begrenzt ist und deren Betrieb vor allem im Sommer Strom liefert, können dezentrale Blockheizkraftwerke (BHKW), die mit Erdgas oder Biogas betrieben werden, hier attraktive Lösungen bieten, um die Stromversorgung im Winter sicherzustellen. Solche Wärme-Kraft-Kopplungsanlagen (WKK-Anlagen) werden besonders dann attraktiv, wenn der Hauptkonkurrent, Strom aus dem zentralen Stromnetz, nicht (oder nur begrenzt) verfügbar ist, einen hohen Kohlenstoffgehalt aufweist oder teuer ist. Darüber hinaus wird gezeigt, dass

lokale WWK-Kraftwerke die Treibhausgasemissionen von zentralen Gas-und-Dampf-Kombikraftwerken bei akzeptablen Gesamtkosten im Betrieb mit Biogas und in Verbindung mit anderen dezentralen Energietechnologien deutlich unterbieten. Ohne Berücksichtigung der Begrenztheit der bestehenden zentralen Energiesysteme sind KWK-Anlagen jedoch hauptsächlich nur für kostengetriebene Energiesysteme, für Großverbraucherstandorte und bei hohen Wärmevorlauftemperaturen attraktiv.

Insgesamt ermöglichen die Daten, die Methodik, das Rechenmodell und die in der Arbeit präsentierten Ergebnisse belastbare und holistische Vorschläge für eine schnelle, erschwingliche, sichere und tiefgreifende Dekarbonisierung des Wohnenergie- und Mobilitätssektors durch dessen Elektrifizierung.

Take-Home Messages

- Das vorgestellte, neu entwickelte Simulationstool auf Basis des Energy-Hub-Konzepts erwies sich als solide und erweiterbare Methodik, den Nutzen und die Schwachstellen der gemeinsamen Elektrifizierung der untersuchten Multi-Energy-Systeme und privater Fahrzeuge ganzheitlich zu bewerten. Die Bewertung solch stark vernetzter Energieanlagen und Fahrzeuge erfolgte anhand der annualisierten Gesamtkosten, der gesamten Lebenszyklus-Treibhausgasemissionen und unter Berücksichtigung vielfältiger systemischer Zwänge sowie wechselnden technisch-ökonomischen Rahmenbedingungen.
- Eine schnelle und tiefgreifende Elektrifizierung des THG- und energieintensiven Wärme- und Mobilitätssektors ist ein praktikabler, wichtiger, robuster und kostenneutraler Weg zur Dekarbonisierung des Schweizer Wohnsektors, der eine Reduzierung der THG-Emissionen um bis zu 70% und ohne zusätzliche Kosten ermöglicht. Dieser sollte daher mit verfügbaren Technologien wie Photovoltaik, Wärmepumpen, Elektrofahrzeugen und biogenen Blockheizkraftwerken so schnell und stark wie möglich forciert werden.
- Unter Berücksichtigung einer saisonal begrenzten und in Zukunft potenziell abnehmenden bestehenden sauberen Stromversorgung aus zentraler Wasser- und Kernkraft erweist sich die Elektrifizierung von Wohngebäuden und privaten Fahrzeugen als schwieriger als bei einer unbegrenzt angenommenen Stromversorgung. Dennoch können dezentrale Energy Hubs den privaten Wärme- und Mobilitätssektor in der Schweiz weiterhin nutzbringend elektrifizieren (Reduktion der Treibhausgasemissionen um ca. 50% bei keinen zusätzlichen Gesamtkosten). Dies geschieht durch den Einsatz einer breiten Kombination von zentralisierten und dezentralisierten Energieanlagen, inklusive Biogas betriebener BHKWs, welche den Nachfragestandorten im Winter bedarfsgerecht Grundlaststrom bereitstellen können.
- Die identifizierten Lösungen sind jedoch komplexe Lösungen welche viele Energieträger, -konverter und -speicher optimal vereinen. Neben allen Vorteilen bringen diese auch Nachteile mit sich, die von Forschenden und Interessenvertretern weiter beachtet werden müssen. Einige dieser Nachteile sind die potenziell unerschwinglichen Investitionskosten und ein erhöhter Anteil an grauen Emissionen der geplanten Energie- und Mobilitätssysteme, die hohe Saisonalität, Intermittenz und Bidirektionalität der Stromversorgung sowie die Verlagerung vom heutigen Erdgasbedarf hin zu einem geringeren aber stark steigendem Biogasbedarf, welche allesamt besonders stromaufwärtige Energieversorger und deren Geschäftsmodelle vor Probleme stellt.

Contents

Abbreviations

Abbreviation	Meaning
ASHP	Air-Source Heat Pump
BT	Base Technology: gas boiler + electrical grid + thermal energy storage + battery
BAT	Battery (stationary)
bat	Battery (mobile)
CCGT	Combined Cycle Gas Turbine
CHP	Combined-Heat-And-Power
CHPP	Combined-Heat-And-Power Plant
CO_{2eq}	Equivalent CO_2 emissions
$CO_{2eq,min}$	Minimal CO_{2eq} emission objective
DG	Distributed Generation
EV	Battery Electric Vehicle
EAC	Equivalent Annual Cost
EAC_{min}	Minimal EAC objective
EG	Electrical Grid
EV	Electric Vehicle
GB	Gas Boiler
GHG	Greenhouse Gas
GSHP	Ground-Source Heat Pump
HP	Heat Pump
HT	Hub Technologies: CHPPs, HPs, PV, BAT
ICEV	Internal Combustion Engine Vehicle
KPI	Key Performance Indicator
MES	Multi-Energy System
MIMES	Mobility including Multi-Energy System
ORH	Ohmic Resistance Heater
PV	Photovoltaic
RET	Renewable Energy Technology
TES	Thermal Energy Storage

Executive Summary

Switzerland, as a country that has pledged to become carbon neutral by 2050, needs to drastically and urgently transform its society towards lower greenhouse gas (GHG) emission levels by making adequate choices on how to better manage and supply its energy demands.

In order to promote this energy system transformation towards lower GHG emission levels while maintaining affordable energy prices and guaranteeing reliable energy supply, the DisCREET projects investigates how decentralized and distributed co-generation, in particular gas-powered combined heat and power plants (CHPPs), can interact with partly intermittent renewable energy technologies (RET) and energy storage systems (ESS) to optimally supply load sites with heat and electricity to power their stationary and e-mobility related demands.

Since the residential energy sector and private individual mobility sector are two strongly GHG emitting demand sectors in Switzerland due to their size and large dependence on fossil fuels, a transformation of these sectors is vital to reduce the ecological footprint of their energy usage in the near-term future. For that matter, two available strategies within these sectors are discussed in this report: technological efficiency increases and fuel switching methods. Their implementation is performed via the installation of technology upgrades such as the replacement of traditionally installed gas boilers with heat pumps for heating and internal combustion engine vehicles for transportation with electric vehicles. These upgraded assets offer increased conversion efficiencies and use electricity as an energy carrier as opposed to fossil alternatives. Therefore, a growth in electricity demand is expected as electrification of the heating and mobility sectors advances. The additional electricity demand in residential settings must hence be met by either more imports from the centralized electrical grid and its associated electricity generation or alternatively must be produced locally via the installation of decentralized electricity generators, such as photovoltaic arrays or co-generation plants. The introduction of these new technologies brings along the advantages and disadvantages of the individual technologies, such as the intermittency and unpredictability of the solar-based electricity generation or the emission-intensity of the gas-based energy supply, which must be evaluated and balanced for an optimal energy and mobility system design. With the goal of an effective, affordable, reliable, and emission-minimal energy and transport system in mind, ideally, the GHG emissions related to the provision of energy are minimized, while simultaneously minimizing total system cost and respecting requirements to satisfy all energy demands, as well as social and technological limitations, such as energy grid constraints.

To efficiently address this complex field of interrelated, sector-coupled objectives and restrictions, the DisCREET project first and foremost developed a software tool allowing better decision-making with regards to optimal energy system planning. The developed tool, which soft-couples simulation and optimization techniques to assess the performance of the underlying energy system, optimally chooses a set of technology upgrades and their optimal operation from a portfolio of available conversion and storage assets as well as energy grids to ensure the optimal supply the residential sector's energy and mobility demands. Therefore, the energy demands of buildings with respect to space heating, domestic hot water, and stationary electricity demand as well as the residents' mobility energy demand are modelled using a combination of datasets and norms as well as commercial and self-developed simulation tools. The optimal matching of demand and supply systems is then provided by computational optimizations based on the so-called Energy Hub concept [1]. An example of such a mathematically described system is given in Figure 1.

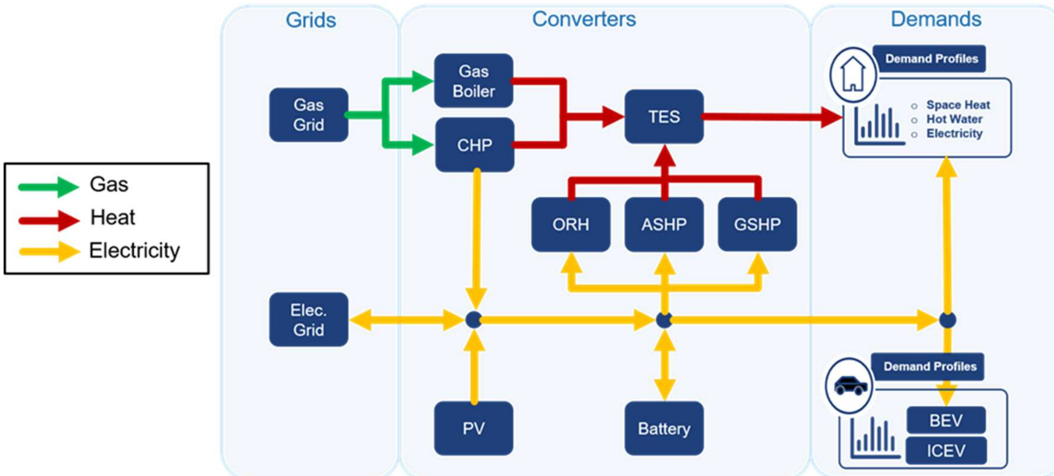

Figure 1: Example of the internals of a decentralized energy system optimization based on the Energy Hub concept. Multiple energy converters (and storages) are optimally chosen, designed, and operated to best utilize energy from the centralized energy grids to supply the demand sites' thermal and electrical energy demands.

These optimizations are carried out from the perspective of a strategic investor, which plans to minimize the total lifecycle cost and lifecycle emissions caused by the design and operation of the assets over a project time of 20 years, thus mimicking the decisions made on the daily by thousands of decision-makers, when planning or replacing their energy and mobility assets. Optimal decision-making with regards to altering the energy supply and private mobility system is hence sought after. A central method utilized to assess the prospective sector-coupled solutions, is the evaluation of partially exclusive trade-offs between cost-optimality and GHG emission-optimality. The application of said methodology via optimization for various residential multi-energy demands, technologies and grid availabilities, energy prices and other techno-economic conditions identifies ideal energy system solutions under changing boundary conditions and generates a robust understanding of the interdependencies in these energy systems. These results are then useful to inform stakeholders on the optimal energy and mobility configurations, designs, and operations based on the technologies' mutual competitiveness and symbiosis to minimize the desired optimization objectives. Fundamentally, four decentralized technology evolutions were assessed in the DisCREET project to comparatively identify advantageous technology combinations. These four technology portfolios are depicted inFigure 2 and represent technology upgrades from today's situation (CVBT) on only the mobility side (to EVBT), on only the stationary side (to CVHT), or on both, the mobility and stationary supply-side (to EVHT).

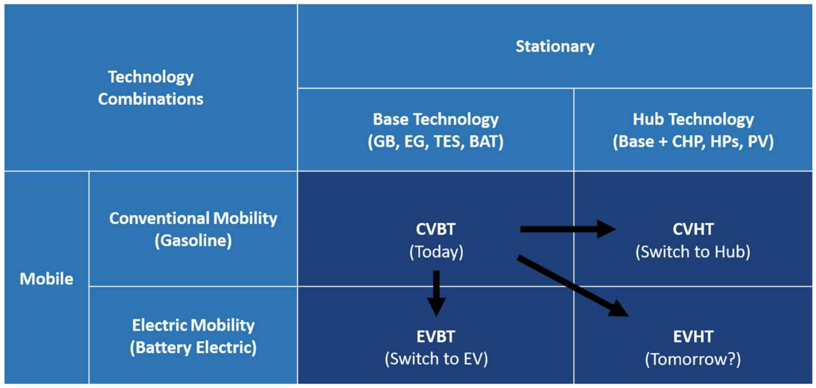

Figure 2: Overview of the main four technology developments assessed within the DisCREET project.

Within the project three groups of results were obtained: Firstly, the data and data sources provided to model residential demand sites and typical supply technologies can form a basis to be used by future research and energy system models. Secondly, the developed methodology to structure, represent, optimize, and analyze the energy systems to be upgraded and optimized can be either applied immediately via additional investigations in the tool's current form or easily expanded with more functionality for future research. Thirdly, the insights generated from the computations can inform stakeholders, such as politicians, researchers, and asset owners, and thus improve the decision-making related to the investment and operation of long-lasting energy supply assets as of today.

The main insights from the project are:

- Switzerland's residential heating and mobility sectors are substantial emitters of greenhouse gases due to their a) size and b) their prominent dependence on fossil energy carriers used in boiler-based heating systems and internal combustion engines. They should hence be transformed to become more efficient and to utilize more renewable supply alternatives for covering their energy demands. This is found attainable and worthwhile.
- The newly developed software tool is a suitable, reliable, quick, and expandable method to holistically assess and recommend associated optimal strategic planning decisions to cost-effectively mitigate greenhouse gas emissions arising in the context of residential energy and private mobility systems. The applied method, that selects optimal designs and operational strategies of assets identified as beneficial, is a bottom-up approach that can provenly easily be scaled up to include single buildings, neighborhoods and districts, numerous conversion and storage assets, and multiple systemic constraints allowing for wide-ranging energy system analysis.
- For the purpose of maximizing GHG mitigation, electrification of the fossil fuel based residential energy and mobility system with heat pumps and electric cars is found to be very advisable in Switzerland, since not only operational but also the total, i.e. including embodied, emissions of these systems can be reduced significantly by up to approximately 70% using available technologies. This is due to a) the high conversion efficiencies offered by heat pumps and electric vehicles over conventional assets, which reduce the required amount of primary energy, b) the identified existing and expandable options to supply additional electricity demand using

sources of low carbon-intensities in Switzerland, and c) the underproportional increases in embodied emissions, when installing new supply assets.

- Further, the emission mitigation via the electrification of heating and mobility is possible without increases in total project cost. In fact, many low-emission solutions were found to robustly offer lower total system cost than comparable reference systems, making increased sustainability an economically attractive option. Only for extremely ambitious GHG mitigation targets, approaching the absolute minimum achievable emission levels to within the last few percent, total costs of the systems increase over reference solutions and eventually reach unreasonable CO_{2eq} mitigation cost values over 500 CHF/tCO_{2eq}.
- If only either the stationary demand or the mobility demand can be electrified, then the stationary electrification typically offers larger benefits in terms of cost-effective CO_{2eq} emission mitigation than electrifying the private mobility sector, largely due to the typically bigger energy demands requested by buildings compared to the mobility demands.
- Direct electrification of heating and mobility with heat pumps and electric cars supplied by the existing electricity grid would be advisable due to the low carbon intensity of Switzerland's existing electricity supply if unlimited amounts of electricity were available. However, the Swiss electricity supply is not unlimited, successful electrification hence needs additional electricity generation. Under limited availability of electricity supply this additional generation is best done by a wide combination of existing and new centralized and decentralized energy supply assets. This optimal set of assets guaranteeing the low-emission and low-cost supply of energy to residential demand sites, depend on the a) size and type of demand site, b) the availability of supply technologies, c) the strictness of the emission mitigation target, as well as d) the techno-economic conditions at hand. Depending on these factors, these systems typically operate heat pumps and electric cars via local PV systems, which are supported by decentralized co-generation plants, the existing centralized grid and possibly newly installed CCGTs and centralized PV plants. With a switch from cost-sensitive to emission-sensitive solutions, natural gas operated assets are phased out, while local biogas utilization in CHPPs increases. At the same time air-source heat pumps are exchanged for more efficient ground source heat pumps.
- Surprisingly, these general trends under limited centralized electricity hold for three tested scenarios of limited centralized electricity supply, representing a) Switzerland's current electricity supply capability, b) its electricity supply after a nuclear phase-out and c) a scenario of no nuclear power and no cross-border electricity exchange.
- Even electrification in isolation of the centralized electricity grid, i.e. without any centralized electricity supply, proves to be beneficial in terms of emission reductions (albeit more expensive) over conventional burner and internal combustion vehicle reference solutions, due to the large efficiency increases and lower emission-intensities in combination with the large flexibility provided by the decentralized means of energy supply, namely local PV and CHPP systems.
- Despite the emission and cost benefits of electrification supported by new means of electricity generation, the electrification of heating and private mobility in combination with optimal de-/centralized supply systems comes at the cost of
  - higher upfront cost (approx. 50% higher despite overall cost reduction) and higher embodied emissions (approx. 200% higher despite lower overall emissions) related to the initial installation of energy and mobility assets,

- higher complexity for planning, installation, and monitoring of the system due to the increased number of technologies used within the interconnected, multi-energy, sector-coupled systems,
- drastic changes to the residential energy demand and centralized energy grid dependency with consequences for the gas and electricity grid operators as well as the upstream utility companies in terms of volumes, peaks, intermittency and seasonality and revenue streams. In particular, gas sales are expected to reduce and switch to biogas, while electricity sales become seasonally varying and peaky.

To accelerate the uptake of such solutions these aspects must hence be addressed.

- Co-generation plants (CHPPs) are an attractive part of the optimal solution of residential energy/mobility system, when
    - the demand sites are large, i.e. the appropriate installation size of the CHPPs becomes large and hence cheaper due to a strong decrease in specific cost with increasing CHPP size, and when cost-minimization is valued more than emission reduction.
    - The demand sites require high temperature heat, as the competitiveness of heat pumps is reduced at high supply temperatures >60°C.
    - The demand sites' thermal-to-electricity demand ratio is similar to the thermal-to-electricity ration of the CHPPs output during large timespans of the year.
    - the alternative options of electricity or heat supply are limited, e.g. by strongly limited roof areas or limited availability of the centralized electricity system (incl. cross-border imports or nuclear power phase-out) or restrictions on heat pump installations.
    - the load demand on the electricity system in winter or the seasonal variation must be reduced, e.g. due to limitations on the operation of the electrical grid. CHPPs are then identified as an ideal technology to produce on-demand, base load electricity in winter, while additionally covering parts of the buildings' thermal demands.

Overall, the data, methodology and insights presented in this work are valuable to illuminate the dark spot of strategic investment planning and therefore energy system planning from the bottom up at the interface of mobility and stationary assets. In literature this is a weakly investigated area with few publications considering the design next to the operational planning of multi-energy systems also comprising decision-making regarding vehicle systems. In particular, the inclusion of embodied emissions into the decisional analysis importantly offers a holistic way to evaluate decisions and should hence be continued.

We wish to see this research head in two directions. Firstly, we would like the insights and methodology to be applied in the decision-making of private, commercial, and public decision-making as soon and strongly as possible to propel the cost-effective emission mitigation within the energy transition forwards using technologies, which are readily available. Secondly, we would like the work to serve other researcher as a basis for further exploration of the co-dependencies amongst decentralized assets as well as their interrelation with the surrounding energy system via replication and expansion of the presented tools. This work has shown that a holistic optimization of the decentralized decision-making coupling the energy and mobility sector is possible and worthwhile for the identification of effective climate change mitigation strategies for systems of various scales and complexities.

1 Introduction

1.1 Background Situation

The Global Climate Crisis

Since the beginning of the industrial revolution, humanity has induced global warming by immensely increasing the amount of annually emitted GHG into the atmosphere [2]. Due to the stability and consequentially the long lifetimes of these molecules they accumulate in the atmosphere, where they contribute to an increasing global temperature via the greenhouse effect. Global warming leads to undesirable consequences for many of the planet's biosystems and should hence be avoided or at least restricted. As there is a near linear correlation between global mean temperatures and the amount of cumulative CO_2 in the atmosphere, fighting global warming is about reducing the atmosphere's CO_2 concentration [3]. According to the same IPCC report, a remaining budget of 400 gigatons of CO_2 may not be exceeded in order to constrain global warming to 1.5°C with a likelihood of 67% starting at the beginning of 2020. At the current global emission rate of 42.2 Gt per year this budget would be exceeded within less than 8 years [4].

Internationally the above and the effects of the climate crisis are becoming more visible and the public awareness for environmental conservation is increasing. Hence efforts to mitigate climate change and its negative consequences are ramping up and implementable and effective emission reduction solutions are urgently sought for globally and locally.

Necessitates Emission Mitigation in Switzerland

The same is true in Switzerland. In 2017, the Swiss population accepted the Energy Strategy 2050. Efficiency increases in the energy sector and the integration of more renewable energy into the supply system are major elements of this strategy, aiming to largely and quickly reduce Switzerland's energy dependency and greenhouse gas (GHG) emissions [5]. Additionally, Switzerland strives to achieve this while discontinuing their nuclear power program [5] in the mid-term, consequently retiring a stable and low-emission baseload generation technology of significant magnitude (35 % of annual generation [6]) in the Swiss power generation, ultimately increasing the need for additional sources of electricity supply.

Done by Transitioning to Intermittent Energy

Further, this anticipated switch from nuclear power to renewable energy carriers, in particular photovoltaics (PV), signifies a switch from baseload generation with high annual load factors to intermittent electricity generation with low annual load factors and strong production variability, marking a fundamental change in terms of how and when electricity is generated. New storage means, such as stationary/mobile batteries or thermal energy storages, and alternative electricity generation pathways are necessary options to smoothen the supply and/or demand side management can be used to alter the local demand in terms of timing and utilized energy carrier to match supply and demand.

To Mitigate Climate Change By Electrification

Additionally, to reduce the emissions in Switzerland the dependency on fossil fuels for delivering energy services needs to be reduced quickly, deeply, and sustainedly. Electrification of the heating and mobility sector via heat pumps (HPs) and electric vehicles (EVs) offers a great opportunity to reduce the ecological footprint of Switzerland and other nations but necessitates the reliable supply of clean and affordable electricity for success. Full electrification of these two sectors will generate challenges for the electricity sector in terms of power quality and quantity, which will need to be addressed.

Important in the Residential Sector including Mobility

Fossil fuels are dominant sources of energy for heating and transport. These sectors must largely be electrified to enable the Swiss energy transition, i.e., the electricity-, heating- and mobility-transition. In particular, heating of residential buildings and private mobility are major contributors to Switzerland's greenhouse gas emission problem due to their large dependence on fossil fuels. Indeed, the residential sector including its private mobility is hence responsible for 40% of the total Swiss GHG emissions [7]. Changes in its energy supply (assets, operation and fuels), may hence mean substantial emission changes on the scale of Switzerland and should therefore be carefully explored and harnessed.

Asset Upgrading & Fuel Switching can have Long-term Effects

Given the long lifetimes of hundreds if not thousands of heating and mobility assets purchased and commissioned on the daily basis just in Switzerland, it is vital to know, which technologies and operational practices can optimally aid the transformation of the electricity-, heating- and mobility-transition in Switzerland. Rigorous planning of these optimal systems should be used to ensure the provision of clean, affordable, and reliable supply of energy while respecting boundaries in terms of system design and operation, energy network constraints, and techno-political conditions. If done correctly, the systems installed today will make contribute to the decarbonization of Switzerland for the next 20 to 30 years.

But Require Energy System Planning and Complex Decision-Making Coupling Multiple Sectors

Planning these system is however complex, due to the multitude of technologies, their individual advantages and weaknesses, their complex coupling within individual and across energy sectors, the spatial and temporal dependency of their conversion efficiencies, the changing techno-economic environment of deployment, as well as the diverse set of energy demands apparent in load sites. Importantly also the criteria by which the energy and mobility systems are evaluated are multifaceted and often involve conflicting objectives, such that trade-offs need to be found. Energy system planning is then the process of identifying solutions which maximize the benefits while limiting the unintended consequences in a field of highly interlinked decisions. To ensure robustness of the investigated solutions varying uncertain circumstances must be tested within the planning procedure. Further, the operation of the supply assets is dependent on the design of the systems, posing an interlinked challenge when planning these systems.

Spanning Decentralized and Centralized Systems

The optimal selection, design and operation of supply technologies is a matter of the assets' competitiveness with respect to certain key performance indicators (KPI), such as cost, sustainability, and energy import dependency compared to the performance of alternative solutions. This is, however, not limited to the competitiveness at the local scale but extends to a competitive environment including the centralized energy supply system. The optimal energy system solution is then evaluated out of all possible implementations considering centralized and decentralized solutions. Once more, the interaction between the system's is heavily interlinked meaning that any decision taken on the local scale, i.e. the decentralized scale, will impact the centralized supply systems and vice versa. Therefore, the impact of changing conditions in one system must be investigated on the other scale.

With Co-generation as a Possible Solution

In this report the special role of co-generation, i.e. the simultaneous supply of electricity and heat, with combined heat and power plants (CHPPs) driven by internal combustion engines in an energy system context is evaluated. CHPPs offer a way to locally produce electricity on demand, which can then be used to operate HPs, to charge EVs or stationary batteries and/or directly supply local electricity demand. This seems particularly attractive during winter nights, when the alternative supply from PV systems is low, i.e. there is a residual electricity demand, and when thermal energy is demanded. Whether CHPPs however substantiate themselves as an attractive energy supply system, depends on the complex and interlinked competition they face from alternative heating systems such as conventional boilers and heat pumps, and from other electricity supply systems, such as PV, battery systems, and the centralized electrical grid.

1.2 Purpose of the project

Decisional-Support for the Energy Transition

To enhance the understanding of optimal sector-coupled, multi-energy systems and facilitate accelerated and well-founded decision-making within the energy transition of Switzerland, the DisCREET project computationally investigates the interaction of stationary energy assets and private vehicles at the energy-/mobility nexus in an integrated manner. On that account, a simulation model has been created that reveals the consequences of long-lasting, bottom-up investments and operational decisions on a local, regional, national scale. By creating this simulation tool that can optimize energy systems configuration, designs and operational strategies in terms of their ecological and economic performance the complex interdependencies of highly interlinked assets can be studied, understood, and utilized to reduce the impact the supply of energy demand has on the environment, while considering changing and limiting supply side constraints. Particularly, the optimal installations and operations of all involved assets are identified, in absence and light of the limited supply capabilities of the existing centralized energy system.

Via a Framework for Holistic Energy System Analysis

A core concept of the work is the development of an assessment framework that analyzes the technologies, their interdependencies as well as their operational effects on neighboring infrastructures holistically. The framework can therefore be deployed to aid effective decision-making with respect to cost-effective climate change mitigation within Switzerland by studying the system’s response to varying input (cf. Figure 3).

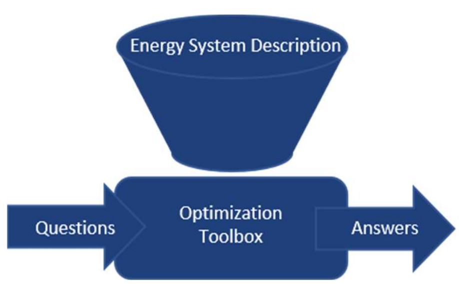

Figure 3: Conceptual idea of an energy system model used for decisional support and strategic guidance of the Energy Transition

To Give Recommendations for Researchers / Governments / Practitioners

The methodology presented and the insights generated are useful to researchers, governmental agencies, and practitioners alike. It is intended to clarify unanswered questions with respect to the best technologies, interdependencies, and sensitivities to scenarios of altered assumptions, to quantify the key issues, to show the untapped potentials, and to highlight current barriers to success within the regional energy and mobility transition in Switzerland.

Since Urgent & Efficient Decision-Making is Needed

Amidst the ongoing global warming and the resulting urgent need to reduce greenhouse gas emissions worldwide, the development of the aforementioned tool facilitates the discussion and decision-making of efficient and effective energy transition pathways by enabling a rigorous cost-benefit analysis. This is needed as a) the decisions are highly interlinked and thus complex to predict without simulation, b) the resources to implement the energy transition are naturally limited. Hence cost-effective measures with little unintended consequences as well as high return on investment are sought after. Thereby resource-efficient, economical, yet ecologically superior transformation pathways can be identified and pursued in a timely manner. Since many of the crucial decisions that impact greenhouse gas emissions for the next years, decades and even centuries are made daily when individuals replace their current heating system or vehicle, the project adapts a bottom-up approach to inform bottom-up decision-making.

1.3 Project Objectives

The objective of the project is to provide a qualitative and quantitative holistic assessment of energy and mobility systems to enable more efficient, effective, robust, and timely decision-making with regards to climate change mitigation via an effective energy transition. For this purpose, several energy technologies and mobility assets are designed and operated to be compared and assessed in terms of their economic and ecological cost and benefit, while considering the limitations dictated by the techno-political-economic boundaries. The simulation tool shall provide guidance as to which assets are to be installed, how they should be designed and operated to maximize their capabilities in terms of effective and efficient energy solutions for regional energy system of today and the future. This is to be done in an integrated manner to allow for systematic comparisons and identification of synergies as well as non-cooperation between technologies and sectors. A particular focus is to be put on co-generation as a means to support the electrification of transport under increasing shares of renewable energy sources. Critical reflection on modelling choices and assumptions will identify crucial elements of such analyses.

Thereby, DisCREET aims to clarify the far-reaching implications of energy-related decisions on a local, regional, and national scale and highlight them to (bottom-up and top-down) decision-makers in order to boost the successful energy transition. The knowledge gained and methodologies established in the project shall be transferable to other regions of the world and hence aid the global energy transition.

The DisCREET project was built in phases to ensure continuous progress towards the objectives of the project. In the initial phase the project's objective was the identification of suitable computational tools, both software and hardware, that allow for the intended optimization at the intersection of stationary and mobile equipment. Then, over the course of the project, the objective comprised the establishment of a basic, minimal working example of the simulation tool, which was built from the ground up. Successively, the project objective switched to expanding the optimization tool's capabilities to facilitate the energy and mobility related decision-making for a growing scope of technologies and system aspects. In doing so, the project was able to generate initial results early in the project, which could then be discussed with and disseminated to the working group in an effort to a) develop the course for further expansion of the tool and b) transfer the insight to stakeholders in the field of energy and mobility transformations.

2 Procedures and methodology

2.1 Concept

The installation /purchase and operation of stationary energy equipment and private vehicles used to cover the residential energy and mobility demands has long-lasting environmental consequences due to the assets' long lifetimes and the energy-intensiveness of residential demands. Hence their deployment should be planned carefully. In doing so, synergies should be utilized and discord avoided. Therefore, this study utilizes computer simulations and optimizations to assess the optimal composition, design and operation of energy and mobility assets, i.e. energy converters, energy storage systems and vehicles, for supplying residential energy and mobility demands when aiming to reduce total cost and total lifetime emissions. An overview of this concept is given in Figure 4.

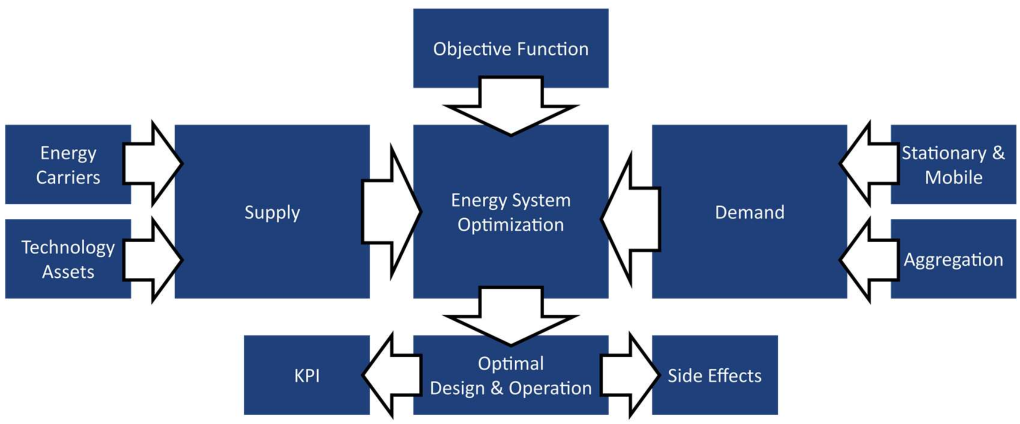

Figure 4: Overview of the toolbox to optimize local energy systems under given supply and demand scenarios. The objective functions can be adjusted to for example minimize the total system costs, or the total system's GHG emissions. KPI = Key performance indicator, which then becomes e.g. the total system costs or GHG emissions.

The depicted analysis is performed primarily from the perspective of residential building owners / residents that have the capacity to decide on the energy supply system and the vehicles to suit their needs. To support their bottom-up decision making the alternative choices are implemented into a tool that investigated optimal decisions for these consumers and informs them on the ideal outcome that suit the consumers' objectives and requirements. Further, analysis can then also inform upstream agents, as the grid operator and the utility company, about this consumer-optimal decision making and the positive and negative consequences for the upstream energy supply, such as the load on the distribution grid.

The consumers make decisions within a regional energy context, i.e. they are influenced by the climatic, governmental, energy-political, technological conditions, etc. under which they can buy and sell energy from/to centralized sources. These conditions and the consumers themselves alongside a set of energy and mobility technologies are modelled and tested under varying boundary conditions to investigate ideal energy systems. Various levels of complexity and scope of the analysis can be tested by changing the amount and types of supply technologies, the level of detail of modelling the adjacent energy system, etc. Thus, the developed tool was continuously developed and expanded to arrive at its current capabilities described below. Hence the simulation tool initially comprised a small set of technologies, a stiff set of boundary conditions and focused purely on the optimization of total project cost at a single building site. Eventually the project comprised of a large set of residential energy technologies, was tested for various buildings and building parks, as well as techno-economic conditions and incorporated the solutions' operational emission performance. Ultimately, embodied emissions were included into the analysis and the scope was expanded to also assess the decentralized energy systems in interaction with centralized energy assets. A purely local, decentralized perspective was found to be limiting due to the interdependencies and competition between the assets on these two scales, e.g. between local CHPPs and centralized CCGTs.

Fundamentally, however, the questions of the project and thus the intended outcome of the analysis tool remained:

- How do we optimally supply residential energy and mobility demand under scenarios of electrification including high penetration of renewable energy carriers and electric mobility?
- Which role does co-generation play alongside other technologies in this context?

2.2 Mathematical Implementation

The above-described tool is implemented as a Mixed-Integer Linear Programming (MILP) optimization model that optimizes the strategic investment for energy assets and vehicles simultaneous to their optimal operation. All necessary code is written in Python. The commercial solver Gurobi is then used to solve a corresponding optimization model.

Depending on the extend of the desired analysis, optimizations can be run on consumer-grade hardware (e.g. 4-core, 8 thread CPU; 16GB Ram), for larger problems involving many assets and in particular many vehicles in combination with numerous runs for sensitivity analyses the computations were run in parallel on the cluster computer Euler. Optimization times for a single energy system design based on an hourly-resolved (8760 time steps) reference year range from seconds to multiple hours.

2.2.1 Multi-energy Energy Hub Concept

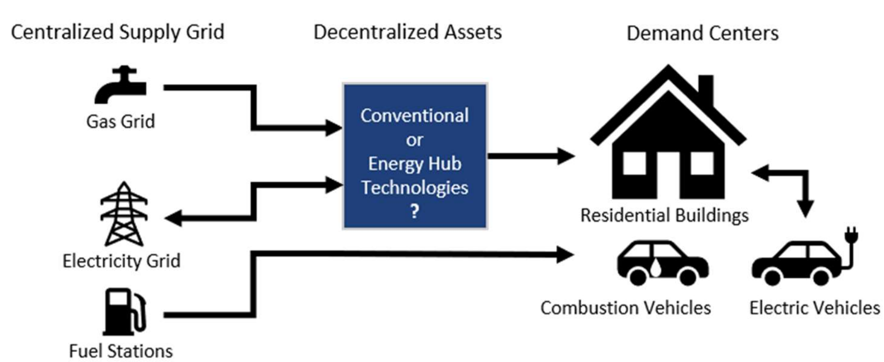

Figure 5: Conceptual overview of the challenge to supply energy to residential demand sites.

The energy systems investigated can be described as Multiple-Input Multiple-Output (MIMO) systems, where a set of multiple energy carriers (e.g. electricity and natural gas) is available to enter the decentralized energy conversion and storage systems, where they are processed and ultimately leave the conversion and storage site to supply multiple energy (and mobility) demands with thermal or electrical energy. Conceptually, this situation can be modelled as an Energy Hub [1,8], as shown in Figure 6. An energy hub is a site at which multiple energy carries are brought together, stored and converted to energy services by a set of supply technologies in order to meet a (multi-) energy demand [1].

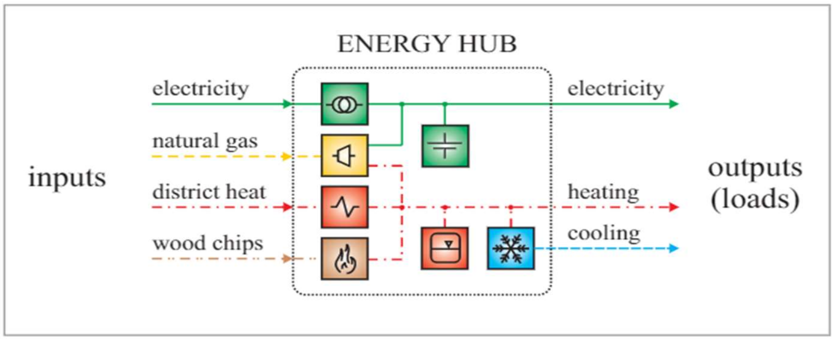

Figure 6: Concept of an energy hub, taken from [1].

A conversion matrix, then describes the coupling, i.e. the relationship guided by the conversion efficiency from one form of energy to another, between all energy inputs and energy outputs [1]. If assets are added to the system the coupling matrix grows, if assets are removed the coupling matrix shrinks in size. Such description enables the combined optimization of technological asset installations and their operation supplying given energy demand profiles.

The developed optimization model is a linear programming tool which optimally selects the decision variables of the program (in this case the design and operation of the respective assets/plants) to optimize an objective function. This objective function can, for example, resemble the total annual cost of a system. In this case, the optimizer will suggest the system configuration and operating schedule that minimizes the overall cost to supply a given set of demand profiles, such as heating and electricity demands. Another possible objective function minimizes the CO_{2eq} emissions related to the supply of the energy demand. In this case the optimizer will not select the system with the lowest overall cost, but the system with the lowest over all CO_{2eq} emissions. Combination of objective functions are possible and are discussed in Section 2.2.2.

In the case of a residential setting, that is intended to be supplied, a set of commonly available technologies might be modelled and optimized. Figure 7 shows such a set of technologies and their interconnection between the energy inputs from the upstream energy grids and the demand side, which includes stationary demands and mobility demands.

At the core, this configuration is the starting point for all subsequent studies. The hub is supplied with energy from the gas and the electrical grid. It converts energy via various conversion and storage devices to the deterministically set energy demands such as electricity for e-mobility or lighting in the building, and thermal energy for space heating and hot water production.

Depending on the case study conducted the technologies, their interaction, the techno-economic conditions, the demands and/or the supply side are varied, allowing the study of a wide and diverse set of optimal solutions.

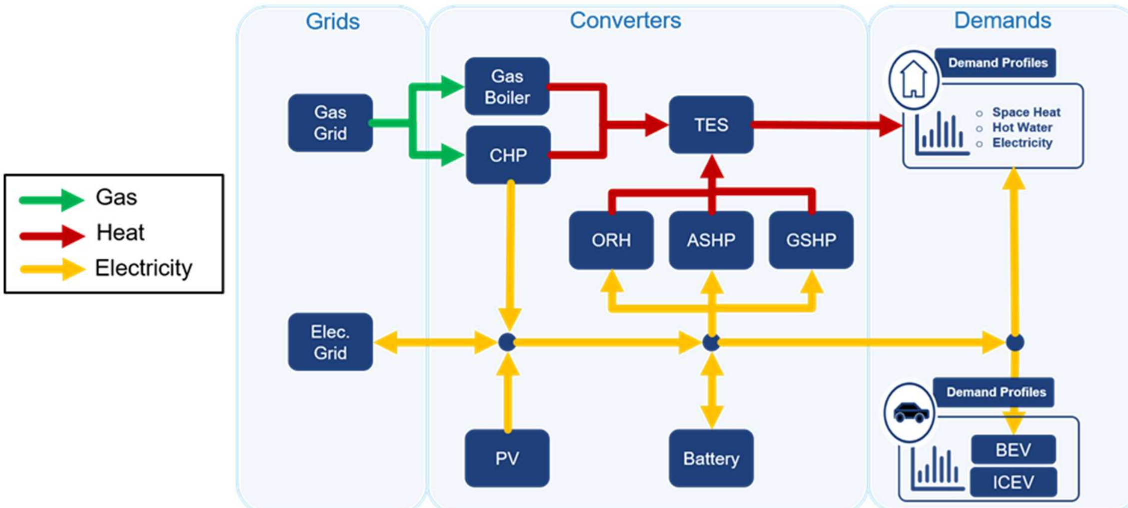

Figure 7: Exemplary set of technologies and interconnections of the supply, demand, converter, and storage units of energy hub under investigation. CHP = Combined-heat-and-power system, PV = Photovoltaics, TES = Thermal Energy Storage, ORH = Ohmic Resistance Heater, ASHP = Air-source Heat Pump, GSHP = Ground-source Heat Pump, BEV = Battery Electric Vehicle, ICEV = Internal Combustion Engine Vehicle.

2.2.2 Objective Functions

In this work the design and operation of the energy hubs is optimized to identify optimal solutions for a set of given conditions. Therein, the objective function defines based on which criterion the solutions are assessed. Different objective functions will lead to different optimal system outcomes. All systems are investigated from the perspective of a strategic investment maker, who plans, invests into, and operates a system for the project duration of 20 years.

2.2.2.1. Single Objective

A single objective is the simplest form of an objective function. The system, i.e. the energy hub, will hence be designed and operated purely towards minimizing (or maximizing) this single objective, while fulfilling certain requirements, such as energy balance constraints. The two major objectives strived for are

- minimal total equivalent annualized cost (EAC_{min})
- minimal total equivalent CO2 emissions ($CO_{2eq,min}$)

Importantly, the equivalent annualized cost represents the total cost for installing, replacing, salvaging, and operating the selected assets for the 20-year project horizon including the discounting. The emission considerations take embodied emissions, caused by the production and installation of the assets, into account next to the operational emissions, e.g. from burning gas. Further, a Well-To-Wheel approach is considered in which the emissions arising from the provision of energy at the conversion assets (Well-To-Tank) is considered in addition to the Tank-To-Wheel emissions. Further, emissions are measured in units of equivalent CO_2 emissions (CO_{2eq}), summarizing the global warming potential of various GHG gases in a single metric. This holistic representation of the energy system allows for holistic decision-making regarding the total cost and the total emissions of an investigated system.

2.2.2.2. Multi Objective / Trade-offs

A more advanced way to assess a system becomes necessary when recognizing that assessing a system based on a single metric is too narrow-minded as energy system planning is a multi-faceted challenge. Hence, combinations of single objectives are sought after. Such multi-objective optimizations therefore enable more complex analyses, by either

- Integrating two (or more) objective functions into a single objective function by addition and inclusion of appropriate weighting factors to each of the individual terms to steer the importance of each subcomponent of the objective function, according to

$$objective\ function = weight_1 \cdot goal_1 + \cdots + weight_n \cdot goal_n$$

or

- Utilizing other techniques to scan the now multi-dimensional solution space. Epsilon-constraint optimization [9] is one of these approaches. There, optimizations are carried out towards a single objective (e.g. EAC_{min}), while the other objective(s) (e.g. CO_{2eq}) are introduced as constraints. These constraints are then tightened in consecutive optimization runs to obtain multiple solutions along a trade-off. Exemplary, optimizations in which the EAC are minimized under the condition that the emissions do not exceed a certain threshold are possible pathways.

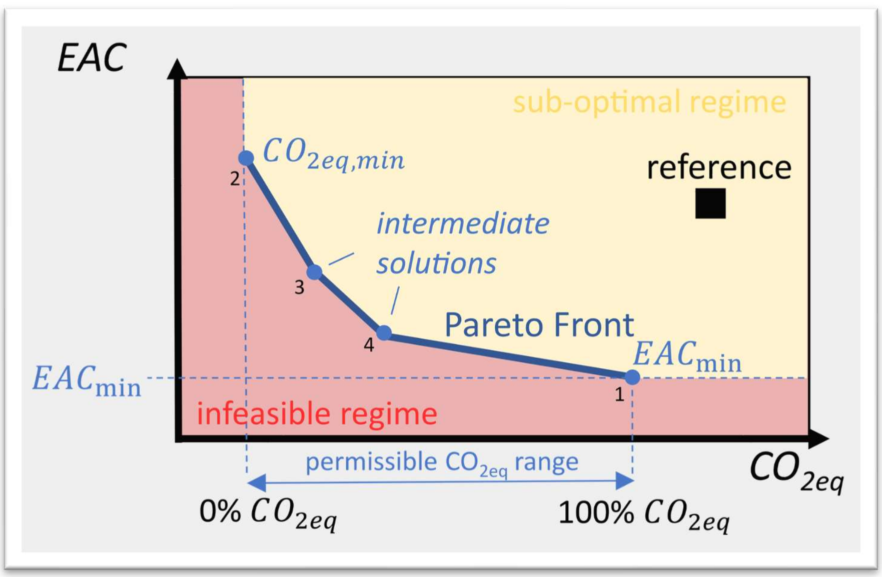

Figure 8: Cost versus CO_{2eq} emission trade-off concept of the analyzed energy hub systems under multi-objective optimization. The smaller numbers along the Pareto Front, i.e. the Pareto optimal trade-off Front, indicate the order of the conducted optimization runs.

Figure 8 shows such economic (EAC) versus ecological (CO_{2eq}) trade-off, where we group the investment cost and the operational cost into the Equivalent Annual Cost [*CHF/year*] and the operational emissions into the annual emissions [*kg(CO_{2eq})/year*] to obtain indicators for the systems' performance. The minimal cost solution (EAC_{min}) and the minimal CO_{2eq} emission solution ($CO_{2e\ ,min}$) set the boundaries of the optimization problem's solution space. One can then search for intermediate solutions by including an additional constraint on the maximum permissible CO_{2eq} emissions and then optimizing for the lowest possible cost at that CO_{2eq} emission level. The slope of the line between two solutions, then expresses the additional expenditure necessary to lessen the CO_{2eq} emissions by the respective amount on the x-axis. Note that a solution below the line of intermediary points or left of the minimum CO_{2eq} emission level does not exist. Hence, these areas are indicated as infeasible solution spaces. Solutions above the line of intermediary points are feasible but not optimal from an ecological and economical perspective, hence labelled "suboptimal".

After the optimization has taken place, a wide set of design and operational parameters can be analyzed. These include the installed capacity of the components, the utilization of those assets, the amount of load hours or full-load hours per year, the number of start/stop cycles per year, etc.

Next to the main objective functions, so-called penalty cost terms can be added to the objective functions to influence the optimal system design and operation in an intended way. This might include penalty cost, which can be understood as inconvenience cost, when low State-of-Charge (SoC) levels of the EV batteries are present. The inclusion of such cost then incentivizes the optimal system to keep the battery SOC levels rather high throughout the optimization horizon. These costs are normally however very small in comparison to the main objective function values.

2.2.3 Decision Variables

As already mentioned, the design and the operation of the energy and vehicle assets are the decisional variables of the optimization. Depending on the chosen assets and operational schedules the energy demand of the residential site is supply by various means. Of course, the installation of assets including vehicles and their operation comes at a cost and causes emissions. Therefore, the optimization carefully chooses the optimal configuration, design and schedule for the stationary and vehicle assets in the energy hub. The more technologies are available to the optimizer, the more complex and interlinked the decision-making becomes.

2.2.4 Constraints

Naturally, the decision making with regards to the decision variables is constrained. These constraints ensure that the energy hubs are operating within their limits, and that certain safety and energy balance conditions are met, etc. The next subchapters give an overview of the applied system constraints.

2.2.4.1. Energy Balances

One of the most important constraints of the design and operation of the energy hubs regards to ensuring the supply of all demanded energy. Since demand / load curtailments are not desirable, the systems investigated in this study are required to supply all residential energy demands at all times. This is ensured by requiring that the sum of supply for each final energy carrier always meets the demand of that final energy carrier.

2.2.4.2. Sizing of Supply Assets

For doing so, a set of suitable energy converters, storage systems and distribution systems must be installed by the optimizer. The optimizer, however, may not necessarily install any capacity of the desired technology. Primarily, the minimum size and a maximum size constraint may apply, to recognize the discrete nature of assets and other constraints, e.g. due to size constraints.

2.2.4.3. Power Limits of the Assets

The installed assets may then only operate within their own capabilities, i.e. they may not operate in excess of their name plate capacity in terms of power input / output.

2.2.4.4. Storage Limits

The storage systems may similarly not store more energy that they were designed for and cannot supply energy when empty.

2.2.4.5. Simultaneous Installation

Further, the simultaneous installation of some assets might not be desirable. This can be excluded. In the simulations conducted only one type of heat pump is allowed to be installed at a time.

2.2.4.6. Simultaneous Operation

Additionally, the simultaneous operation of some assets might not be desirable or feasible. For example, the electrical energy storage systems (EV batteries and stationary batteries) may not charge and discharge at the same time.

2.2.4.7. External Constraints

Lastly, other external considerations may limit the design and operation of the optimal energy hub. This might include limitations to the amount of energy and power that is available to be imported from the centralized energy grids due to e.g. seasonal variations in supply or the amount of power than can be fed to the centralized energy grids as a function of the line capacity connecting the residential sites to the centralized supply system.

2.3 Perspective, Scale & Scope

Within energy system planning the perspective from which the decisions are analyzed and made matters. In this work the chosen perspective is mostly the bottom-up perspective of a residential player, e.g. a consumer or prosumer or building planner, that oversees making investment and operational decisions with the goal of minimizing the total cost and total emissions over the project horizon of 20 years in mind. Given an exogenous set of boundary conditions, like energy prices, technology cost and conversion efficiencies, climatic conditions, etc., the bottom-up player assesses potential implementations of the multi-energy hub including mobility and decides to alter the demand site's technology and vehicle portfolio at the beginning of the 20-year project horizon to her/his advantage. One the one hand, the self-affecting consequences of this decision-making can be evaluated on the key performance indicators, given by the numeric values of the objective functions, but also on other metrics that are not explicitly regarded or constrained in the objective function but rather an implicit consequence of the decision-making, such as the operating hours of certain assets or their operational cycles in case of storage assets. Hence, insights on a multitude of aspects with respect to consumer-optimal energy hubs can be found. On the other hand, the consequences of this bottom-up decision-making on the upstream energy system and suppliers can be studied. This includes how the pro-/consumer's net energy demands affect the utilization of the centralized energy grids and hence the revenue streams of the upstream suppliers.

Since the analysis focused on the strategic decision-making the temporal resolution of the operation is chosen to be one hour. Therefore, 8760 timesteps and thus 8760 operational decisions are considered per year and per technology. This reference year is then assumed representative for the next 20 years, so that the overall assessment for the strategic investment can be made.

From a spatial perspective, residential buildings in the City of St. Gallen are taken as a basis for the investigations, for which the *Office for Environment and Energy*[1] of the City of St. Gallen provided a building dataset to be used in the study. This building selection defines the boundary conditions for the optimizations and also for the preceding computations of the energy demand profiles. Since the optimizations are computationally intensive, this is done for a subsample of all residential buildings rather than for every building in the area (see Figure 9).

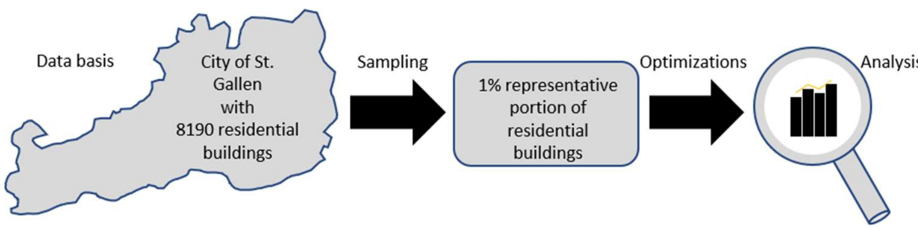

Figure 9: Residential buildings in the City of St. Gallen and the investigated subset

2.4 Demand Side Modelling

To optimally size and operate the multi-energy hubs to match the residential energy demands, the residential energy demands must be known. Several data sources and energy demand models are combined to derive the full set of energy demands.

2.4.1 Stationary Demand Modelling

The stationary energy demand comprises three types of the energy demands that the residential buildings assets must fulfil on an hourly basis. This includes energy demand for space heating (SH), domestic hot water (DHW) and electricity (ELEC) to operate non-heating related devices. Figure 10 summarizes this utilized basis from which the annual, hourly-resolved energy demand profiles were

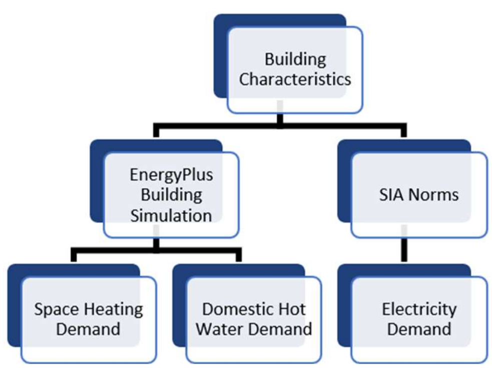

Figure 10: Logic flow to derive the stationary energy demand profiles.

[1] Amt für Umwelt und Energie, Stadt St. Gallen, Vadianstrasse 6, 9001 St. Gallen, Switzerland.

derived. This work was kindly carried out by Dr. James Allan[2] using the method described in [10] to provide the stationary energy demand profiles used in the subsequent optimizations.

2.4.2 Mobility Demand Modelling

Next to the stationary energy demands, the residents of the buildings demand energy to satisfy their mobility needs. From the understanding of how much, to which locations and when residents desire to travel, mobility energy demand models can then be used to translate this mobility demand into an energy demand to be supplied by the energy system/hubs. The mobility demand model was developed by Giacomo Pareschi[3], who derived corresponding person-based mobility demands from the Swiss Mobility and Transport Microcensus [11] and provided kindly this data for the DisCREET project. The process is described in more detail in [10].

The mobility energy demand models then translate a kilometer-based mobility demand into an energy-based mobility demand. This conversion is either simply a multiplication with reference specific energy demands of the vehicles or – in the case of electric vehicles - is dependent on the ambient temperature, resulting in higher specific energy demands in winter and summer, i.e. in non-reference ambient conditions). The overview of the mobility energy demand modelling is given in Figure 11.

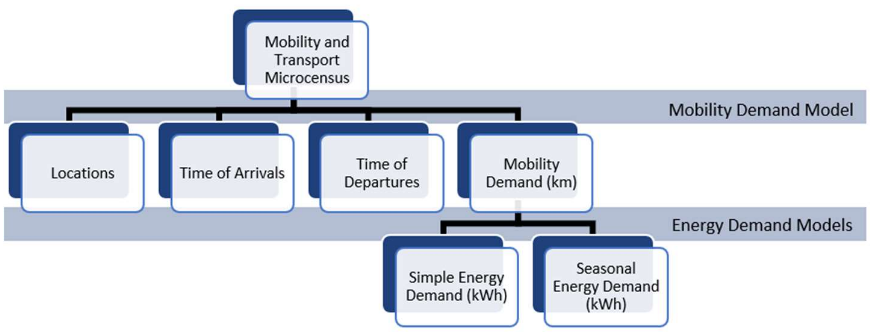

Figure 11: Overview of the mobility and its energy demand generation.

2.5 Supply Side Modelling

To supply the energy demands for stationary and mobile needs, an array of ambient energy sources, energy grids to exchange energy with, and centralized/decentralized supply technologies is available. This section describes the components and corresponding models used to describe the supply side. Two components for the successful description of the supply systems are necessary: 1. appropriate technology models, 2. appropriate data to fill the models.

2.5.1 Ambient Conditions

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[2] Urban Energy Systems Laboratory, Swiss Federal Laboratories for Materials Science and Technology, Empa, Überlandstrasse 129, 8600 Dübendorf, Switzerland

[3] Aerothermochemistry and Combustion Systems Laboratory, ETH Zurich, Sonneggstrasse 3, 8092 Zürich, Switzerland

The two important ambient conditions affecting the supply side of the energy system are the ambient temperature and the solar irradiation impinging the solar systems supplying the energy hub. The ambient temperature influences the conversion efficiencies of some of the converters significantly. For example, the air-source heat pumps (ASHPs) efficiency (Coefficient of Performance) is largely impacted by the ambient temperature variations. Further, the amount and timing of solar radiation defines the solar energy potentially useful to the energy hubs and can significantly vary from location to location, especially on an hourly basis due to cloud coverage, fog, etc. Meteonorm software was used to extract the necessary weather data.

2.5.2 Energy Grids / Import and Export Sites

The centralized energy grids are the backbone of any grid-connected energy hub. The energy hubs can draw various forms of energy from these centralized grid components to supply their energy demands, but – in the case of bi-directional grid connections – can also export energy to the centralized energy system. Three main centralized energy grids are considered: the natural / biogas grid, the electricity grid, the fuel station system. The electricity grid is the only bi-directional grid.

Naturally, importing energy from the centralized grids leads to operational cost for the consumer. Also, with the import of energy the consumers take on responsibility for the associated environmental footprint of the energy imports. Vice versa, for the export of energy to the grid revenue and emission credits can be obtained, which promote the feed-in of excess electricity to the grid rather than local curtailment.

2.5.3 Decentralized Technology Assets

2.5.3.1. Stationary Assets

A multitude of technologies is available at the energy hubs to convert and store the energy flows into final energy for the consumers. The technologies utilized in the presented studies which can cover the buildings' thermal energy demands are gas boilers (GBs), combined heat and power plants (CHPPs), air-source heat pumps (ASHPs), ground-source heat pumps (GSHPs)[4]. These all feed into a mandatory thermal energy system (TES), from which the users draw the desired thermal energy. The decentralized technologies that potentially supply the electrical demands are CHPPs, photovoltaics (PV), stationary battery systems (BATs) and mobile battery systems (bats) within present electric vehicles (EVs). These decentralized assets operate in synergy or dysergy with the centralized grids.

Most assets are modelled as constant efficiency devices that take in energy at a specific rate and convert this energy into one or multiple alternative energy streams. This is true for the GBs, CHPPs, GSHPs, CCGTs, centralized grid components and the charging / discharging of energy storages. Other assets cannot be well described by constant efficiency models. Especially the COP of the ASHPs is sensitive to variations in the supply temperature. Further, the centralized and decentralized PV systems can be modelled with temporally varying conversion efficiency, as their output is also a function of the cell temperature and the irradiation, both time-dependent variables themselves.

[4] Other technologies such as oil-based or wood-based heaters, solar thermal collectors as well as district heating are beyond the scope of the study and hence not further discussed. These could however be integrated in future research to expand the capabilities of the tool.

The installation of decentralized energy system is subject to costs and embodied emissions. These are modelled based on a fixed portion upon any installation of an asset and a variable portion dependent on the selected size of the asset, which leads to decreasing specific investment cost and embodied emissions with increasing system size, such that the common concept of economies of scale can be represented in the model. Figure 12 shows the idea of this modelling approach exemplary for the investment cost of the systems. An analogous concept is used for describing the embodied emissions arising from the installation of the stationary assets and vehicles.

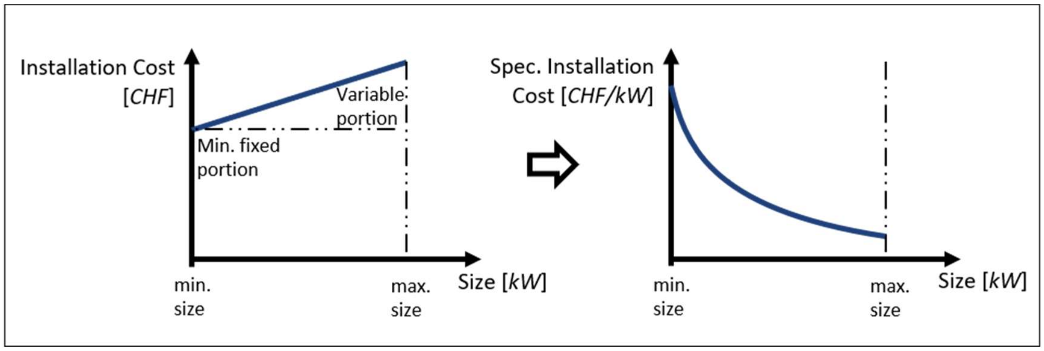


Figure 12: Modelling size-dependent characteristics into the energy system optimization via Boolean-controlled installation.

2.5.3.2. Mobile Assets

A motorization rate of 46% is assumed in the presented studies. Two types of vehicles are investigated in this study: gasoline powered combustion engine vehicles (CVs) and electric vehicles (EVs). These differ in terms of their specific energy demand per kilometer, and with regards to refuelling / recharging. Where CVs are supplied by gasoline stations and are assumed to fill their tank whenever needed at typical consumer prices without restrictions, EVs are restricted to charge at charging locations during their downtimes.

2.5.3.3. Charging Systems

Two EV charging station locations are distinguished. EVs mostly charge at home, where the EVs typically spend large portions of their time and charging cost are generally relatively low. Smart Charging, i.e. a temporal shift of the charging process to financially or ecologically attractive times (e.g. times of low time-of-use tariffs or times where excess PV energy is available), is enabled at home. The optimizer uses this flexibility and the knowledge of desired driving schedules to choose the optimal charging strategy. In rare cases, when long trips are demanded by the drivers without sufficient stops at home, the EVs can additionally charge at public charging stations to top up their vehicles and hence enable these long trips without the need of increasing the battery capacity of the EVs to extreme values. EV charging at public charging stations is assumed to be rapid, i.e. without consequences for the travel schedule, and to emit equal amounts of electricity per kWh charged as the import of a kWh to the energy hubs causes.

2.5.4 Centralized Technology Assets

In addition to the decentralized technologies, centralized equipment can contribute to supply the local energy demands.

2.5.4.1. Existing Systems

This can partially be accomplished by the current, i.e. the existing, centralized energy supply systems, which comprise the gas grid, the fuelling stations and the electricity grid described in Section 2.5.2. If any of these systems, however, are stressed beyond their supply capability, supply system failures or load curtailments would be expected. Hence, supply from the existing centralized system is constraint to certain supply capabilities.

2.5.4.2. Capacity Expansion

In case additional electricity is required beyond the supply capability of the existing centralized electricity system and to avoid such faults or curtailments, the existing systems can be expanded by new centralized generation capacities. Since the gas and fuel supply are assumed to be non-critical in times of electrification, the electricity supply alone is considered limited in some scenarios. Under this assumption the electricity system can then be expanded by new generation capacities. The two additional, centralized supply systems modelled are

- Centralized Combined Gas Turbine Power Plants (CCGTs)
- Centralized PV installations (Cen. PV)

When installed, these additional generation technologies compete to supply consumers with energy at the local scale. Naturally, this energy production is not only subject to installation/embodied and operational cost and emissions of the plants but also to the charges and losses brought about by the utilization of the electrical grid infrastructure connecting the power plants and the final consumers.

2.6 Reference vs. Optimized System

To properly judge the cases of optimized supply systems, a reference system is designed and operated to which the optimized energy hub solutions can be compared.

This reference system with base technologies is a simple system that represents a typical energy supply situation in residential buildings. Four components are present in all reference cases:

1. Natural gas (NG) operated gas boilers (BG) which are supplied by the upstream gas grid (g-grid) and heat the buildings' space and water to specification.
2. A small thermal energy storage system (TES), i.e. a hot water storage tank.
3. A unidirectional connection to the upstream electrical grid (EG) from where the reference system draws all the electrical energy needed to supply the buildings electricity demand.
4. Gasoline based internal combustion engine vehicles, also described as conventional vehicles (CV), which fuels up at regular gas stations.

The optimized system of hub technologies can select additional supply components from a portfolio of technologies and thus potentially has redundant ways to supply the site's energy demands. These technologies include

1. Combined heat and power co-generation plants (CHPPs) based on gas-driven reciprocating internal combustion engines.

2. Heat pumps (HPs) that offer the choice of air-sourced (ASHP) or ground-sources (GSHP) heat pumps.
3. Photovoltaics (PV) that can be installed on the roof of the residential buildings.
4. Stationary battery systems (BAT) that can buffer excess electricity to increase autonomy or self-consumption ratios, as well as to perform arbitrage.

In cases of electrified mobility, the CVs are exchanged for EVs, either partially or fully. Depending on the available mode of charging (unidirectional or V2G/V2H systems) the batteries installed in the EVs offer another buffer system for storing excess local electricity or even a redundant energy supply pathway for the buildings, that may act in competition to stationarily installed battery systems.

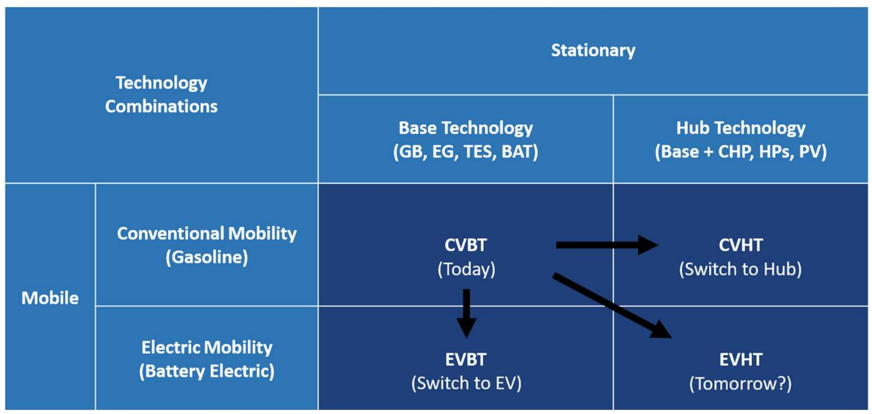


Figure 13: Cases of technology upgrades originating from the reference system with base technologies.

Figure 13 shows the main development possibilities all originating from today's reference case, which includes conventional vehicles and base technologies for stationary energy supply (CVBT) towards three alternative scenarios comprising various combinations of alternative technologies. An analysis of the three electrification pathways is presented in the next sections.

3 Results & Discussion

The following sections present and discuss the main results from the work conducted in this project. Results partially come from the work done with the working group and are partially based on two related works [10] and [12].

3.1 Energy System Data

To be able to set up the optimizations, the supply side data to fill the supply side models must be known. Therefore, a literature review was performed to identify common conversion and storage technologies, their efficiencies, lifetimes, typical installation and operating cost as well as embodied emissions and operational emissions etc. Figure 14 gives an overview of the supply technology data needed.

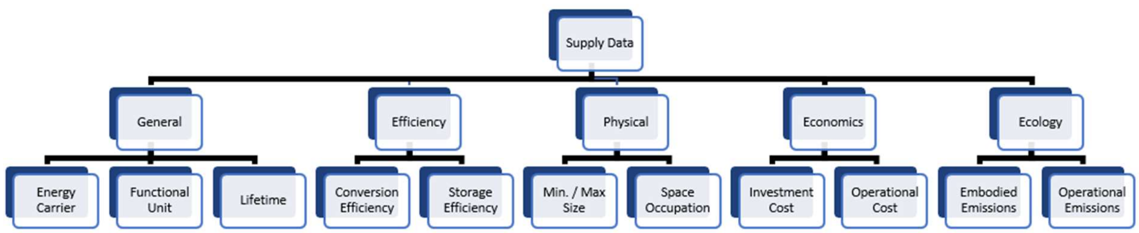


Figure 14: Overview of the necessary data to describe the supply side appropriately.

In particular the data on the installation cost of small-scale energy conversion technologies as well as embodied emissions of these energy assets was hard to find, as there are few resources that summarize these aspects, especially for the Swiss context and for an extensive list of technologies. The most helpful resources for this matter were [13–18]. From these and other sources indicated in [10], the data related to the installed technologies and its energy demand was derived. Further, the grid related data was identified. Figure 15 shows the supply system data used in the publication [10] on which the subsequent results presented in Section 3.3 are based.

Table 3
Supply overview of energy grids. For detailed information on the CO_2-intensity derivation of the e-grid see Section A.5.

Grid Type (direction)	Grid Cost	Cost Type	CO_2-intensity (excl./incl. upstream process) [$kgCO_{2eq}$/kWh]
g-grid (import)	0.079 CHF/kWh + 2.20 CHF/kW/month[1] [65]	Energy + power	-/0.228 [66]
e-grid (import)	0.2368 CHF/kWh (high: Mo-Fr: 7–20 h, Sa:7–13 h), 0.1748 CHF/kWh (low) + 7.50 CHF/month [67]	TOU energy + monthly fee	-/0.040
e-grid (export)	0.083 CHF/kWh (high: Mo-Fr: 7–20 h, Sa:7–13) 0.062 CHF/kWh (low) [68]	TOU energy (monthly fee incl. in import)	-/-
f-grid (import)	1.635 CHF/liter [69]	Energy	0.265 kg/kWh ([70–72])/0.331 kg/kWh (increase by 25% for upstream CO_{2eq},[73])

[1] This monthly fee is modelled as an annual fee for computational tractability.

Table 4
Supply overview of stationary converter technologies. For detailed information on the data sources and derivation of investment cost of some assets see Sections A.6.1–A.6.3.

Converter Tech.	Input, Capacity Unit	Conversion Efficiency (η_{th}, η_{el})	Lifetime [years]	Size constraints (s_{imin}, s_{imax})	Investment Cost [CHF]	Embodied CO_2 [kg CO_{2eq}]
GB	Gas, kW_{gas}	95%, 0%	20	2, 100	18′712 $\cdot b_{GB}$ + 455$\cdot s_{GB}$ [cf. Section A.6.1]	0 $\cdot b_{GB}$ + 51 $\cdot s_{(GB,th)}$ [74]
CHPP	Gas, kW_{gas}	60%, 30%	20	3, 100	13′985 $\cdot b_{CHPP}$ + 869 s_{CHPP} [cf. Section A.6.2]	3′750 $\cdot b_{CHPP}$ + 100 $\cdot s_{(CHPP,el)}$ [74]
ASHP	Electricity,kW_{elec}	$COP_{ASHP}(t)$, 0%	20	1, 100	30′442 $\cdot b_{ASHP}$ + 1′998 $\cdot s_{ASHP}$ [cf. Section A.6.1]	2′329 $\cdot b_{ASHP}$ + 75 $\cdot s_{(ASHP,th)}$ [74]
GSHP	Electricity,kW_{elec}	COP_{GSHP}, 0%	20	1, 100	26′975 $\cdot b_{GSHP}$ + 7′575$\cdot s_{GSHP}$ [cf. Section A.6.1]	1′806 $\cdot b_{GSHP}$ + 72 $\cdot s_{(GSHP,th)}$ [74]
EG_{dis}	Electricity,$kW_{elec\,in}$	0%, 99%	80	0 or building dependent	0 $\cdot b_{EG_{dis}}$ + 200 $\cdot s_{EG\,dis}$ [75]	0 $\cdot b_{EG_{dis}}$ + 0$\cdot s_{EG\,dis}$
EG_{chr}	Electricity,$kW_{elec\,in}$	0%, 99%	same asEG_{dis}	defined byEG_{dis}	(incl. in EG_{dis})	(incl. in EG_{dis})
PV	Radiation,m^2	0%, 19%	30	6.4,$size_{roof} \cdot f_{roof\,max}$	4′436 $\cdot b_{PV}$ + 228$\cdot s_{PV}$ [cf. Section A.6.3]	0 b_{PV} + 254 $\cdot s_{PV}$ [74]

Table 5
Supply overview of stationary storage technologies. For detailed information on data sources and derivation of BAT investment cost see Section A.6.4.

Storage Technology	Input, Capacity Unit	Efficiencies (η_{chr}, η_{dis}, η_{sdr})	Lifetime [years]	Size Constraints [kWh] (s_{imin}, s_{imax})	Investment Cost (fix + variable) [CHF]	CO_{2eq} (fix, variable) [kg CO_{2eq}]
TES ($T_H = 60\,°C$, $T_C = 20\,°C$)	kW_{th}, kWh_{th}	100%, 100%, 1%/h [74]	20	3,1000	1′685 + 12.5 $\cdot s_{TES}$ [74]	31 + 4.7 $\cdot s_{TES}$ [74]
BAT (stationary)	kW_{el},kWh_{el}	95%, 95%, 0.1%/h [74]	10	2,100	7′482 $\cdot b_{BAT}$ + 449 $\cdot s_{BAT}$ [cf. Section A.6.4]	0 + 157 $\cdot s_{BAT}$ [74]

Figure 15: Excerpt on the supply technology data from [10]. For the respective references please refer to the original document.

3.2 Energy Model Results

The results from the stationary and mobility demand models are now presented.

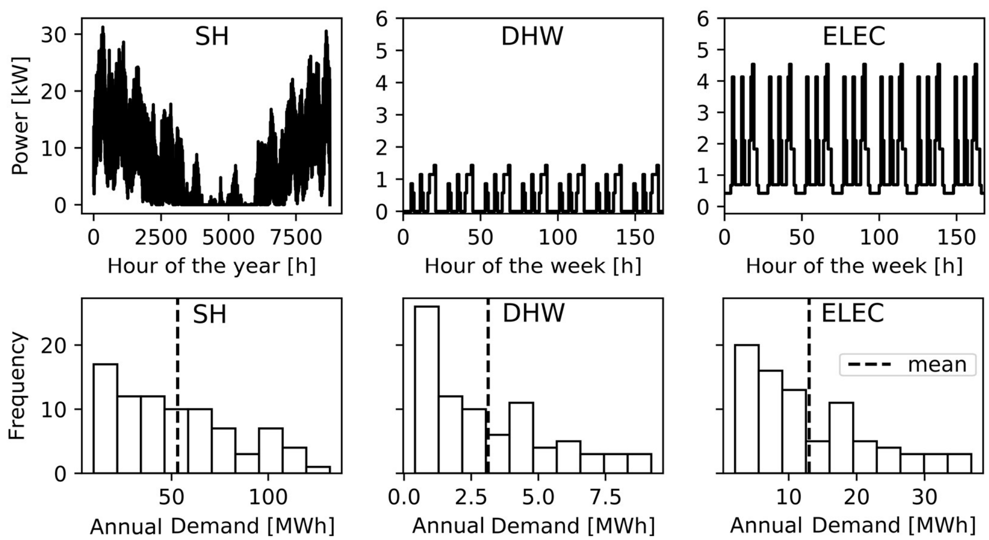


Figure 16: Modelled stationary energy demand profiles as an average of 83 randomly selected residential buildings in the City of St. Gallen. Taken from [10]. SH = Space Heating, DHW = Domestic Hot Water, ELEC = Electricity (Stationary)

Figure 16 shows the temporal evolution of stationary energy demand over time derived from the stationary energy demand simulations averaged over 83 randomly selected residential buildings (33 Single Family Houses + 50 Multi-Family Houses), housing 637 residents, in the City of St. Gallen. Additionally, the distribution of annual energy demands is given. Space heating (SH) is the largest energy demand by a wide margin and exhibits a strong seasonal variation. The stationary electricity demand (ELEC) is the second largest demander but is constant throughout the year.

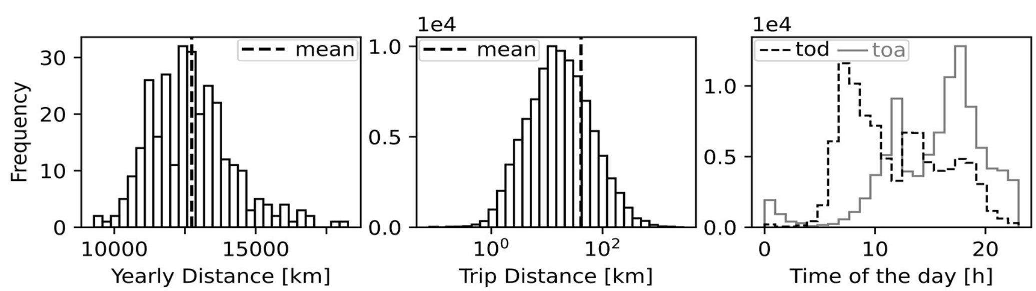


Figure 17: Results from the mobility demand model, mimicking the mobility habits of the residents. Taken from [10]. tod = time of departure (from home), toa=time of arrival (at home). Trips are home-to-home trips.

Figure 17 depicts the mobility behaviour of the investigated residents, including typical annually driven distances, trip distances, and arrival and departure times at the home location. Although highly stochastic, general trends in mobility behaviour are clear that the energy hubs must cover.

3.3 Optimal Investment and Operation of Multi-energy Hubs under Unlimited Grid Supply

Given the available supply technologies and demand profiles, the energy hub optimization was run under the assumption that the existing centralized energy, and in particular the electricity system, is always available unrestrictedly.

3.3.1 Optimal Asset Sizing for EAC_{min}

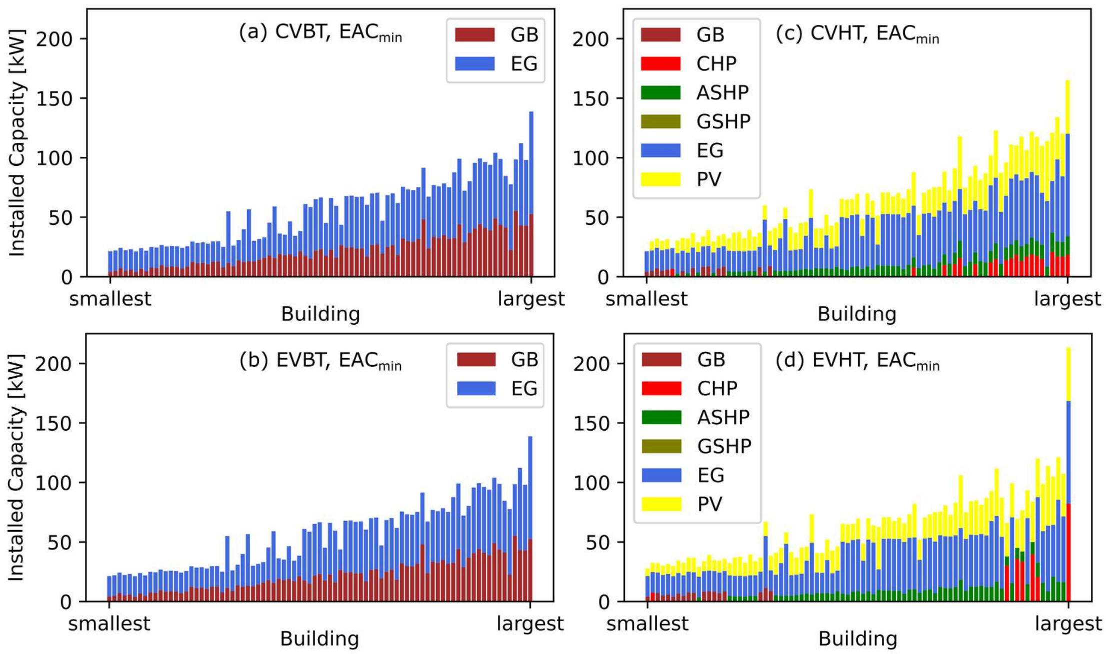


Figure 18: Optimal asset design for 83 randomly selected and sorted-by-size residential buildings under 4 technology combinations aiming at minimal EAC. Taken from [10]

The corresponding optimal decentralized energy supply system designs can be identified from the results and are shown in Figure 18. When the wide set of decentralized supply assets is available (HT cases), a multitude of technologies is installed in the cost-minimal designs. Depending on the size of the supplied buildings, the optimal technologies vary. CHPPs are shown to contribute to low-cost solutions, when the buildings are large, which translates to large thermal and electrical energy demands. If additionally EVs are present instead of CVs, the electricity demand on site increases as the EVs are mostly charged at home. With respect to the optimal installation of CHPPs this leads to the installation of larger CHPPs if CHPPs present attractive supply assets, but also reduces the frequency in which CHPPs are part of the cost-optimal solutions. Interestingly, in four cases the CHPPs take over the complete energy supply in combination with local PV systems and heat pumps. In these cases, the connection to the electrical grid is renounced to reduce cost such that islanded systems designed.

3.3.2 Optimal Asset Sizing for $CO_{2eq,min}$

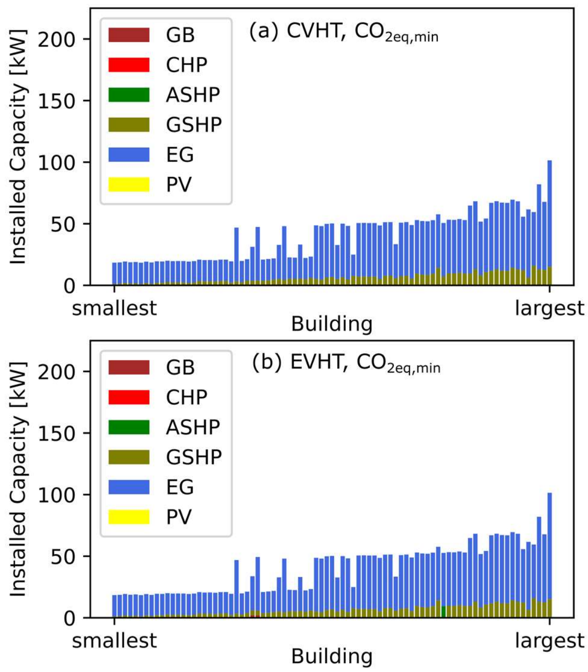


Figure 19: Optimal Asset Design for 83 randomly selected and sorted-by-size residential buildings at minimal-emission conditions. Taken from [10]. Note that BT cases are not optimized for minimal emissions as the standard set of technologies offers little to no flexibility for optimization.

Under emission-minimal requirements the natural gas driven CHPPs are not part of the optimal asset design. Ground-source heat pumps that are supplied by the abundantly available electrical energy system are almost unanimously the best solutions.

3.3.3 Pareto Fronts – Reference Conditions

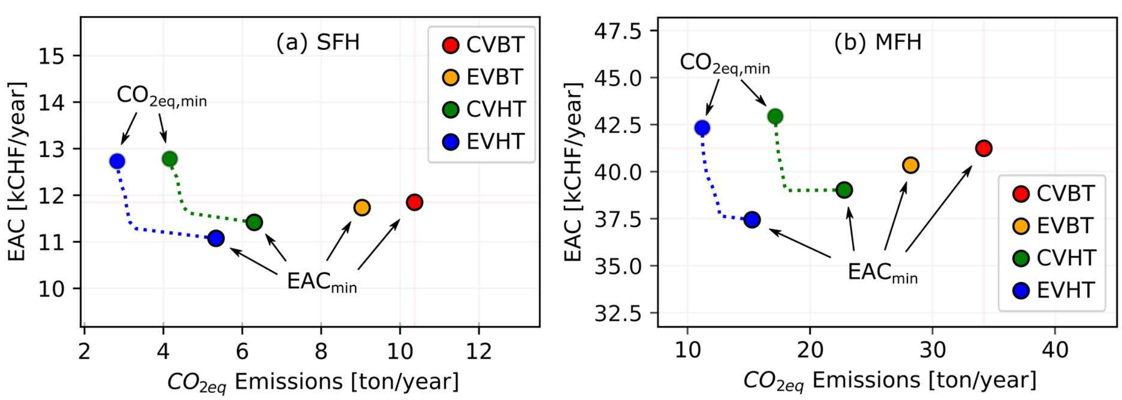


Figure 20: Pareto-optimal trade-offs between cost- and emission-minimal solutions as an average for the 33 SFHs and the 50 MFHs for 4 technology cases. Taken from [10]

Figure 20 shows a comparison of the key performance indicators (EAC and CO_{2eq}) averaged over all buildings per building type for 4 technology cases each under reference conditions[5]. Solutions exhibiting low costs and low emissions simultaneously are sought after. Since these objectives are however partially conflicting trade-offs (indicated by the Pareto Fronts) can be found. From the plots it becomes clear that solutions including EVs and (hub technologies (HTs), outperform all other solutions in terms of minimal achievable cost and minimal achievable emissions. If only either stationary upgrades or mobile upgrades are allowed, then stationary upgrades offer more benefits than the switch from CVs to EVs in terms of cost- and emission savings. Interestingly, - on average - substantial emission savings are possible at net negative total cost if cost-efficient technologies, including CHPPs for larger buildings, are installed on a wide basis. If emission-reductions are considered more important than cost-reductions, then further emission reductions are possible compared to the cost-minimal emission levels. These additional emission savings are relatively larger for smaller (SFH) buildings.

[5] Reference conditions are 3% interest rate, 47’000 CHF investment cost of the average (electric) vehicle, 11 kW EV charging rate, 100% mobility demand factor, and a CO_{2eq}-intensity of 40 grCO_{2eq} / kWh_{el} from the centralized grid.

3.3.4 Pareto Fronts – Non-Reference Conditions

To investigate the results' sensitivity to altered input parameters a sensitivity analysis was conducted by varying multiple parameters deemed particularly uncertain and interesting. The effects on the KPI can be seen in Figure 21. Here the results are averaged over all investigated residential buildings.

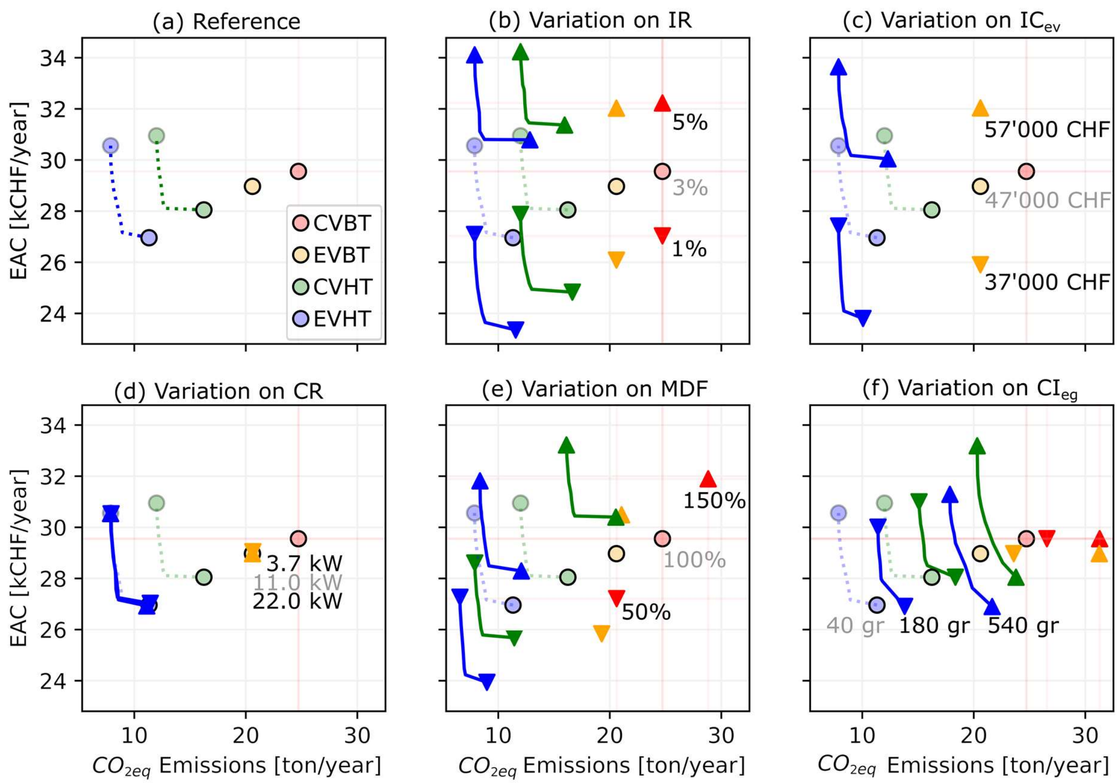


Figure 21: Pareto-optimal cost-emission trade-offs under uncertain parameters. IR = Interest Rate, IC_{ev} = Investment Cost of an EV, CR = EV Charging Rate at home location, MDF = Mobility Demand Factor, CI_{eg} = Carbon-Intensity of the electrical grid. Taken from [10]

The variation of parameters allows the study of shifts and tipping points in the results. Interestingly, the overall trend of EVHT outperforming CVHT outperforming EVBT outperforming CVBT seen in subplot

(a) is valid for all tested parameters, at least when focusing on emissions. In terms of cost, this is also true, except for when the investment cost of the EVs is dramatically increased. In this scenario, the solutions involving CVs offer less expensive, yet more polluting solutions than their EV including counterparts.

3.3.5 Emission Breakdown

Taking a closer look at the composition of the emissions, Figure 22 shows the average breakdown of emissions for the reference conditions and a set of non-reference conditions. The salmon-colored columns indicate the usage of natural gas in the energy hubs. While gas is extensively used in the BT cases (within the GBs) to provide heating, gas is only marginally used in cost-minimal solutions in HT (CVHT and EVHT) cases and quickly phased out when the importance of cost-based analysis is reduced from 100% towards emission focused objectives. The exception is shown in subplot (c) where the usage of gas is increased under intensifying emission standards. In this case the carbon-intensity of the electrical-grid is unattractively high, so that natural gas based (incl. CHPP) offer ecological benefits over electricity-based systems. In Switzerland, with its clean electricity supply gas-based system hence have a tough standing, when electricity is assumed abundant and clean. Investigations including biogas and limited electricity supply are discussed in Section 3.4. Interestingly, a large share of emissions – particularly in the cases where HTs are present – stems from the mobility sector.

3.3.6 Investment Hurdle

Despite the stark advantages of the solutions with electric vehicles, energy hub technologies or even both upgrades combined, these solutions also bring along some downsides. The initial investments required to install these systems trump the initial cost required to install the reference solutions many times over. Figure 23 shows that even the conservative installations aiming at minimal EAC (columns 2-4),

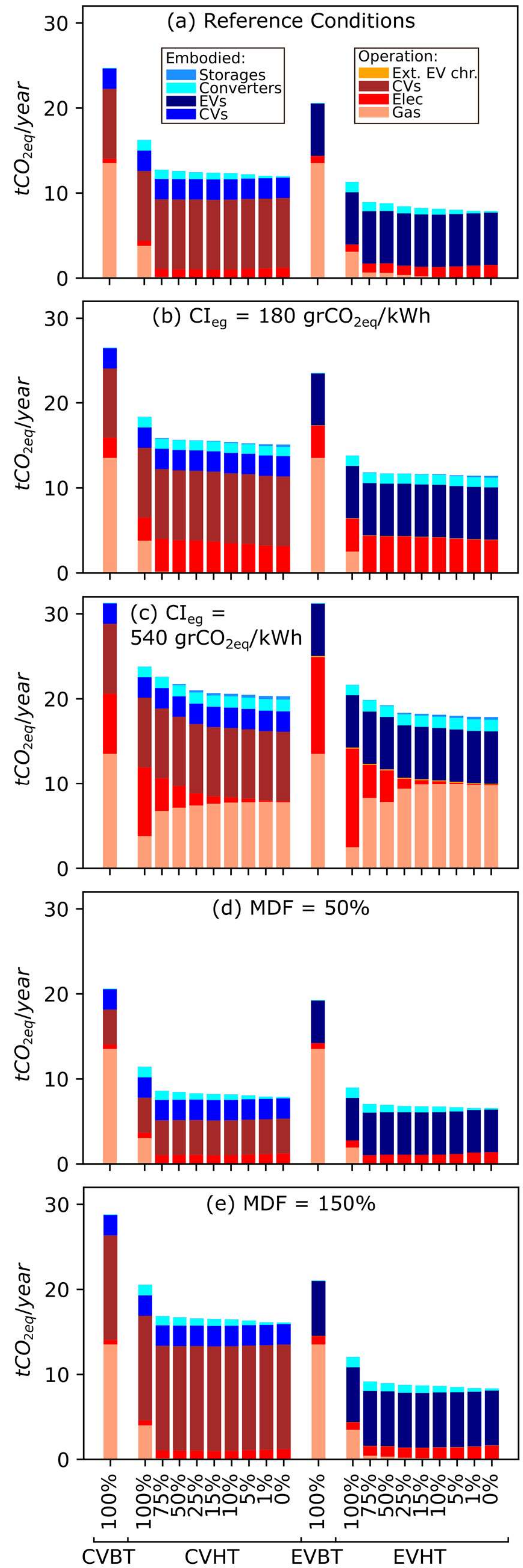


Figure 22: Emission Breakdown for a selection of non-reference cases over the emission target variation and for 4 technology cases. Taken from [10]

require additional non-negligible initial funds over the reference case (column 1). Under high carbon-intensities of the electrical grid and thus largely gas-based installations, the required initial investment for the stationary equipment can even increase by a factor of 3.

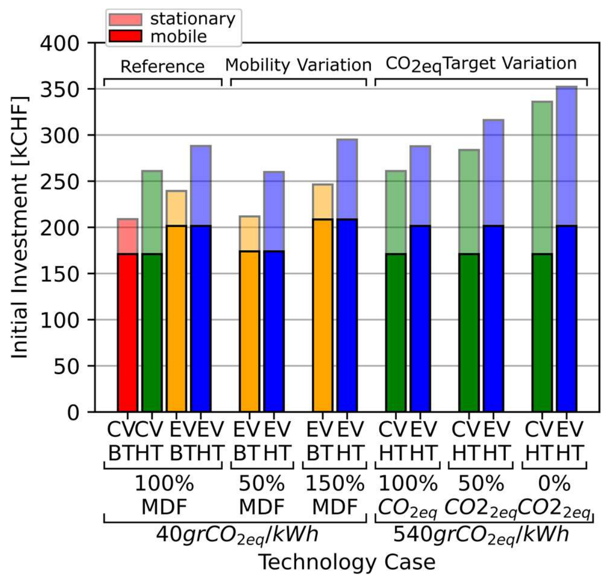
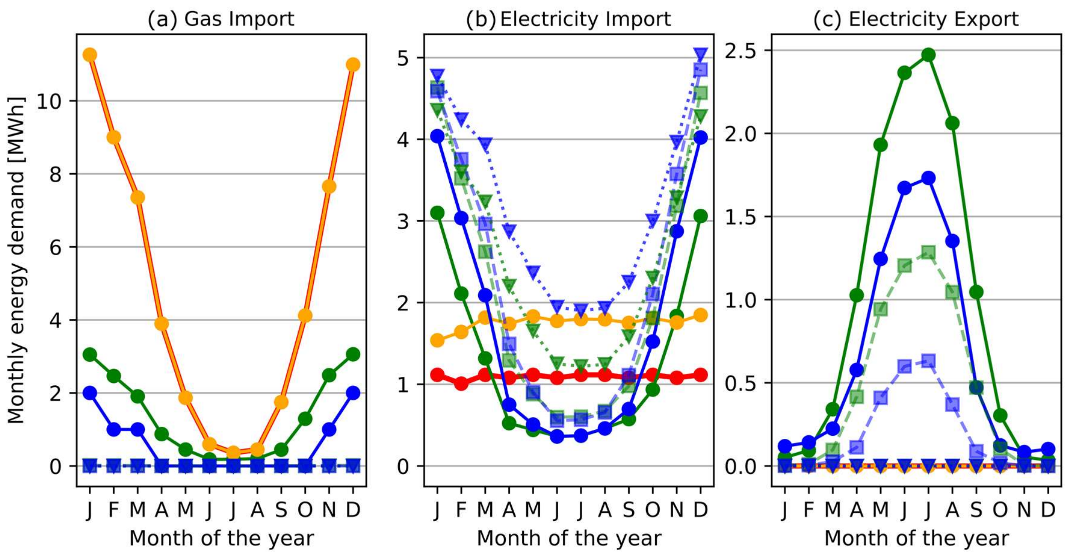


Figure 23: Initial Investments to install the respective systems enabling the emission reductions for various settings. Taken from [10]

3.3.7 Monthly Energy Import / Export Dependency

An important consideration with regards to the installation of optimal energy systems is the effect that this system will have not only on the investors or operators of the system themselves but the effect of these systems on the adjacent or upstream actors. With the installation of new stationary technologies and the utilization of different vehicle types, the demand for certain energy carriers shifts considerable. Figure 24 displays this shift on energy import and export dependence on a monthly basis. Here the annual amount of energy demand and the temporal placement of the energy demand throughout the year can be seen. As to be expected by the low installation of gas-based assets in all but the BT cases, the demand for natural gas plummets towards zero. Contrary, the demand for electricity imports increases compared to the CVBT case by nearly a factor of 3 in extreme cases. Additionally, the formerly level electricity import demand succumbs a strong seasonal variation that was previously characteristic for the gas import demand. This is caused by the strong seasonality of heating demand formerly supplied by gas given assets and now primarily covered by electricity-consuming heat pumps. Further, the observed maximization of PV array installations on the building roof tops manages to reduce the dependency of electricity imports in summer compared to reference levels, yet cannot majorly contribute to resolving the local demand for electricity in winter, which overall leads to an intensification of the seasonal variation in electricity demand and supply.

With regards to the electricity export, the HT solutions that deploy local electricity generation devices, i.e. PV and/or CHPPs, may export excess electricity to the grid in return for a feed-in remuneration. Most of this export happens in summer, then the electrical demand for heating via heat pumps is low and the PV generation is high. During winter, electricity export is much reduced compared to summer, resulting in insignificant contributions towards supplying the grid.



		(a)	(b)	(c)
100% CO_{2eq} (EAC_{min})	CVBT	59.3 MWh	13.1 MWh	0.0 MWh
	CVHT	16.6 MWh	15.1 MWh	11.8 MWh
	EVBT	59.3 MWh	21.1 MWh	0.0 MWh
	EVHT	13.6 MWh	20.7 MWh	7.8 MWh
25% CO_{2eq}	CVHT	0.1 MWh	25.4 MWh	5.6 MWh
	EVHT	1.6 MWh	27.1 MWh	2.3 MWh
0% CO_{2eq} ($CO_{2eq,min}$)	CVHT	0.0 MWh	30.2 MWh	0.0 MWh
	EVHT	0.0 MWh	38.2 MWh	0.0 MWh

Figure 24: Monthly Import/Export Dependence of the optimal energy solutions as the sum of energy demands from all residential buildings. Taken from [10].

3.3.8 Hourly e-Grid exchange

The interaction with the electrical grid on an hourly basis is depicted in Figure 25. In the reference case (subplot (a)) electricity is only imported from the e-grid to the demand site. The addition of EVs (subplot (b)) increased the load on the e-grid in terms of energy demand, power demand and variability of demand via the convenience of charging EVs during low-cost hours. The introduction of HT technologies (without EVs), shown in subplot (c), leads to very strong and peaky export peaks resulting from the installation of large PV systems on the buildings' rooftops. For increasingly environmentally friendly solutions, the amount of export and thus the peakiness is reduced (cf. subplots (e,g)) due to the reduction in installed PV systems. Under the assumption of clean and abundantly available electricity supply from the centralized grid, local PV systems offer a comparatively worst emission performance, since embodied emissions are considered in these simulations. When EVs are present in the HT solutions (EVHT), they increase the demand for local electricity. This leads to increased imports from the centralized electricity grid in terms of power and energy but reduces the dependency on electricity exports in terms of power and energy.

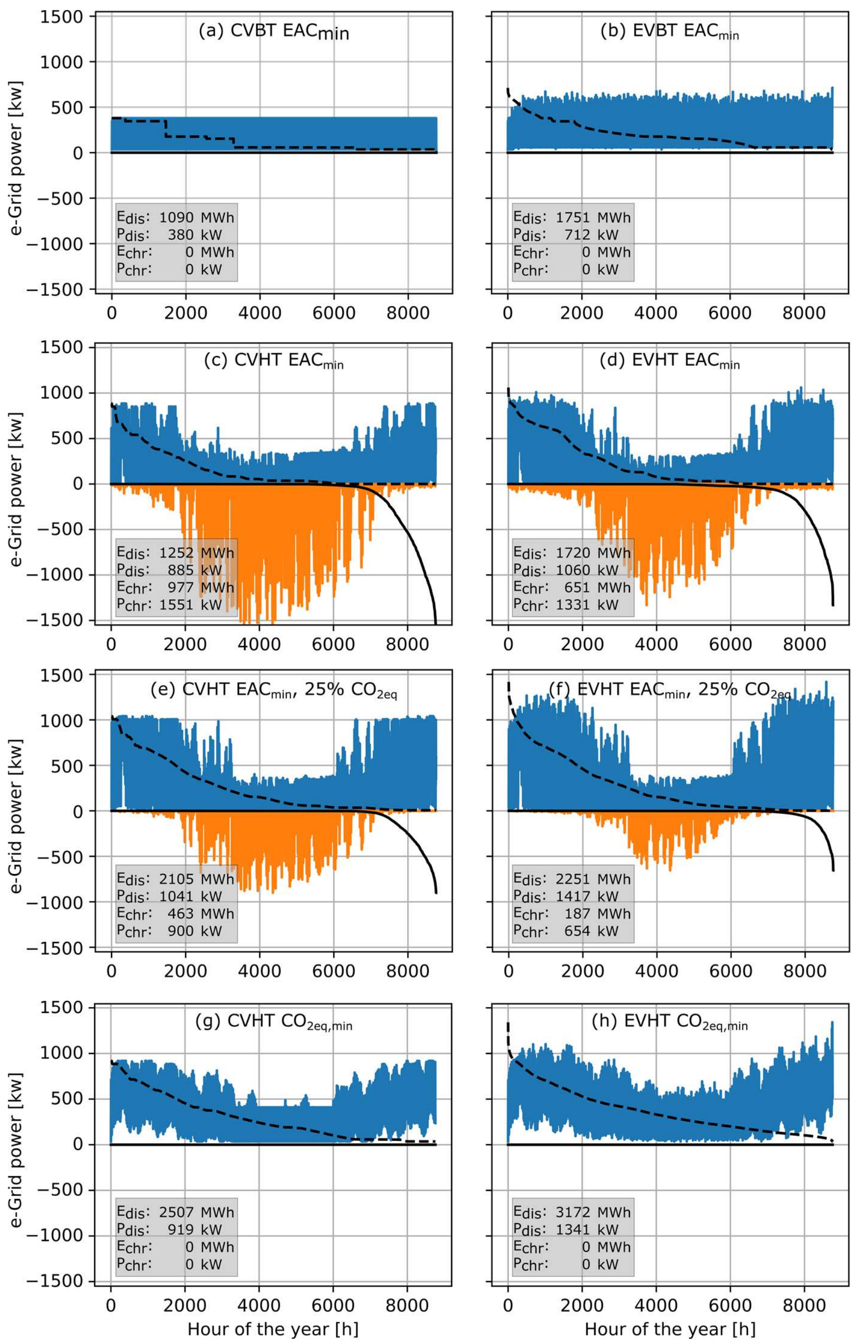


Figure 25: Hourly e-grid exchange (import and export) for various technology cases and emission reduction ambitions as the sum of exchange from all investigated residential buildings. Taken from [10].

3.3.9 Intermediate Conclusions

In this segment the methodology to simultaneously optimize the installation and operation of both, stationary and mobile assets, under consideration of total cost and lifetime equivalent emissions was shown to be feasible and deliver interesting results. For a total of 83 residential buildings of varying sizes, the optimal combined energy and mobility systems were identified and the trade-offs between cost and emission performance shown for 4 distinct technological portfolios ranging from a) a reference case to b) the electrification of only the mobility systems, c) the electrification / upgrade of only the stationary systems and d) the combined electrification of the mobility and the stationary system. It was found that the electrification is very attractive in terms of emission reductions and also in terms of cost savings for all technology portfolios. The joint electrification of the mobile and the stationary equipment however produced by far the most beneficial results, followed by the upgrades of the stationary components. An uncertainty analysis further proved the results to be robust against the variation of various techno-economic and electrical grid-related parameters, suggesting that full electrification should be sought after. Nevertheless, some barriers, like the increased upfront cost and the largely increased dependency on the electrical grid, was highlighted. Natural gas driven CHPPs play a role in large buildings when cost-reduction is the primary objective, as they can offer relatively inexpensive supply of energy given that their sizes are large and hence specific investment cost low. When emission reductions are however considered, the relatively emission intensive supply of energy from CHPPs is quickly replaced by heat pumps and the supply of electricity is done via the clean Swiss electricity grid. And while the switch to electric vehicles does influence the optimal supply composition, CHPPs gain attractivity in some cases, while they lose attractivity in others. A clear, generalizable indication of more electric vehicles leading to more CHPPs was not found. However, there seems to be a window in which a certain number of EVs at a load site make CHPP supply economically attractive.

To investigate options for a more realistic, system-aware electrification of the decentralized demand sites, rather than the egocentric electrification of load sites without consideration of the potential upstream supply problems, the investigations in the next section include restrictions on the centralized supply system, which consider that a systemwide rollout of electrification must comply with limits to the availability of centralized supply.

3.4 Optimal Investment and Operation of Multi-energy Hubs under Limited Centralized Electricity Supply

Unlike previously assumed the electricity supply from the centralized electricity grid is not unlimited but limited by the installed generation and transmission capacities as well as seasonal fluctuations. A full electrification of heating and vehicles assets driven by the existing electricity demand is hence likely not possible. In this segment, the effects of a limited electricity supply on the optimal design and operation of energy-hubs are investigated. The presented results are largely taken from [12] for details and additional interpretation please consult this document.

3.4.1 Limited Availability of the Centralized Supply System

The Swiss centralized electricity supply system is largely based on electricity generation from hydro and nuclear power plants. Other generation technologies contribute little to the overall electricity supply. Due to the low marginal cost of electricity generation from these generation types, the respective power plants will operate at high annual load factors but still limit their production according due to external conditions or maintenance schedules. In these times of short supply Switzerland utilizes its cross-border transmission grid to satisfy its electricity demand. In times of oversupply, this interconnection can also be used to export electricity to neighbouring countries. In recent years, Switzerland has been a net importer in winter and a net exporter of electricity in summer, mostly influenced by the timing of the hydrological cycle.

As seen in the previous part of the report, electricity demand is deemed to increase due to electrification, when focusing on cost- and even more emission-reduction. Switzerland will hence need to supply more electricity to the final customers, either centrally or decentrally. Additionally, the planned nuclear phase out and/or the potential desire to reduce Switzerland's dependence on electricity imports/exports with neighbouring countries might worsen today's supply situation.

To investigate these effects five distinct energy supply scenarios are defined and the energy hub optimizations carried out in their presence:

1. Unlimited electricity supply (reference): unl
2. Standard electricity supply: std
3. Electricity supply without nuclear power: nN
4. Electricity supply without nuclear power nor cross border elec. exchange: $nNnE$
5. No electricity supply from existing centralized electricity systems: non

To model the three partially limited electricity supply scenarios, data on the historic production and the installation of power plants in Switzerland was utilized. The nationally available electricity is then split amongst the various energy demand sectors, i.e. industry, services, residential. In terms of energy the residential sector receives 33% of Switzerland's electricity [6] and it is assumed that 50% of the available

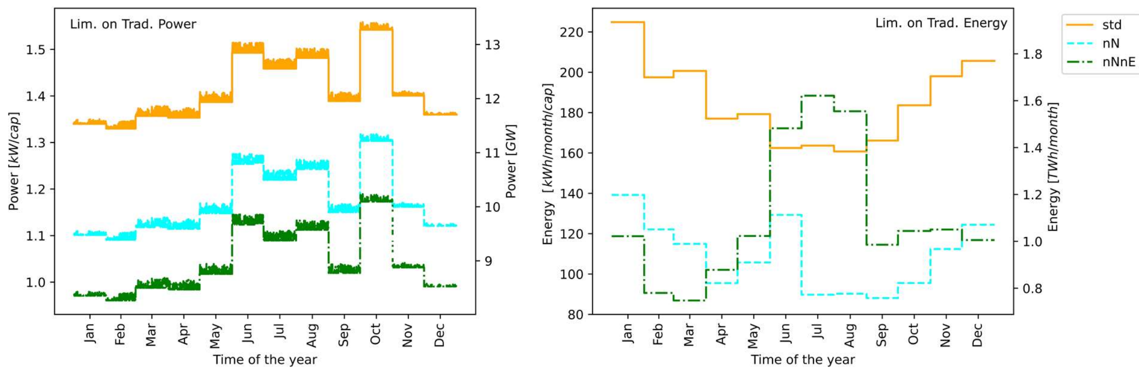


Figure 26: Three partially limited supply scenarios from the existing centralized supply system. left: power limitation, right: energy limitation. Taken from [12].

power is available to the residential sector. An equal share of the electricity available to the residential sector is then assigned to every person in Switzerland. The resulting limitations on power and energy availability on a per person and on the national level are shown in Figure 26.

3.4.2 General Model Setup

The described electricity supply scenarios concern the limitations of the existing electricity system (Trad. Grid). To cope with the anticipated increase in electricity demand, new centralized generation plants can be installed in combination with decentralized energy systems. These comprise centralized PV

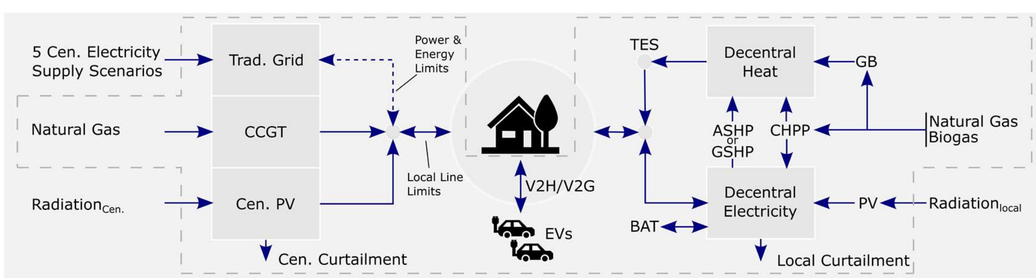


Figure 27: Optimization setup of centralized and decentralized energy systems. Centralized systems comprise 5 scenarios of existing electricity generation, as well as new production means from Cen. PV and CCGTs. Taken from [12].

systems (Cen. PV) and natural gas based combined cycles gas turbines (CCGTs). Since complete electrification of the stationary as well as the mobile assets was identified the most promising yet challenging in terms of electricity supply, the following sections focus only on the EVHT case, i.e. energy hubs with the full set of decentralized (and centralized) assets available and vehicles being electric vehicles. These optimal hub-based results are then compared to a reference solution with only basic, traditional technologies and conventional vehicles.

3.4.3 Conceptual Model Updates

The new centralized supply systems as well as the centralized supply constraints have been added to the optimization tool. Further, since the electrification of residential energy systems, does not only increase the demand for electricity but also introduces large seasonality into the system, a special focus was put on the assets that are susceptible to seasonal variations. Therefore, a) the PVs' conversion efficiency was updated to account for temperature and radiation influences, b) the energy demand requested by the EVs is modelled dependent on ambient temperature, such that EVs will consume more electricity than under reference conditions during cold and hot days.

Moreover, to increase the onsite flexibility and to modernize the capabilities of the energy hubs, the EV charging procedure was updated from unidirectional smart charging to also allow for V2H/V2G discharging of the vehicle batteries.

Additionally, the option to curtail excess electricity onsite was implemented.

Besides, the centralized CCGT is assumed to run on 100% natural gas, the decentralized CHPPs runs either on 80% natural gas and 20% biogas or on 100% biogas. The inclusion of a 20% biogas share in the standard natural gas product reflects the current standard gas product offered by the energy provider of the City of St. Gallen. For simplicity, the shared decentralized gas mix will nevertheless be referred to as natural gas, due to the large share of natural gas in the product.

Lastly, by the implementation of small penalty cost as an addition to the objective functions, which do not affect the overall results significantly, grid feed-ins are made more attractive than local curtailments, and a higher SoC in the vehicles is preferred to a low SoC.

3.4.4 Numerical Model Updates

The numerical values of the supply data were slightly updated from the previously presented data. Particularly, it was updated to include the necessary data corresponding to the conceptual model updates, e.g. the inclusion of new centralized supply systems. Figure 28 and Figure 29 indicatively show the updated supply data from the conversion technologies and grids respectively. For detailed information readers are referred to the original document.

Table 5: Technology data of the optimized energy converters, based on [36,58], otherwise specified or own assumption.

Converter Tech.	Input; Capacity unit	$\eta_{th,i}$; $\eta_{el,i}$	LT_i	$s_{min,i}$; $s_{max,i}$	$IC_{fix,i}$	$IC_{vari,i}$	$CO_{2eq,em,fix,i}$	$CO_{2eq,em,vari,i}$
GB	NG / BG; kW_{gas}	95%; $-$	20	$2; \infty$	$18'712 \cdot b_{GB}$	$455 \cdot s_{GB}$	$0 \cdot b_{GB}$	$51 \cdot s_{GB,th}$
CHPP	NG/BG; kW_{gas}	60%; 30%	20	$3; \infty$	$13'985 \cdot b_{CHPP}$	$869 \cdot s_{CHPP}$	$3'750 \cdot b_{CHPP}$	$100 \cdot s_{CHPP,el}$
ASHP	Electricity; kW_{elec}	$COP_{ASHP}(t); -$	20	$1; \infty$	$30'442 \cdot b_{ASHP}$	$1'998 \cdot s_{ASHP}$	$2'329 \cdot b_{ASHP}$	$75 \cdot s_{ASHP,th}$
GSHP	Electricity; kW_{elec}	$COP_{GSHP}; -$	20	$1; \infty$	$26'975 \cdot b_{GSHP}$	$7'575 \cdot s_{GSHP}$	$1'806 \cdot b_{GSHP}$	$72 \cdot s_{GSHP,th}$
Local PV	Radiation; m^2	$-; \eta_{PV,local}$	30	$6.4; A_{roof,usable}$	$4'436 \cdot b_{PV,loc.}$	$228 \cdot s_{PV,loc.}$	$0 \cdot b_{PV,loc.}$	$254 \cdot s_{PV,loc.}$
EG	Electricity; kW_{elec}	0%; 100%	80	$f(building\ type)$	$0 \cdot b_{EG}$	$200 \cdot s_{EG}$	$0 \cdot b_{EG}$	$0.1 \cdot s_{EG}$
Cen. PV	Radiation; m^2	$-; \eta_{PV,Cen.} \cdot \eta_{grid}$	30	$0.001; \infty$	$0 \cdot b_{PV,Cen.}$	$167 \cdot s_{PV,Cen.}$ [59]	$0 \cdot b_{PV,Cen.}$	$254 \cdot s_{PV,Cen.}$
Cen. CCGT	NG; kW_{gas}	$-$; $60\% \cdot \eta_{grid}$	30	$0.001: \infty$	$0 \cdot b_{CCGT}$	$598 \cdot s_{CCGT}$ [60]	$0 \cdot b_{CCGT}$	$0.1 \cdot s_{CCGT}$

With $COP_{GSHP,real} = \zeta_{GSHP} \cdot \frac{T_{TES_h}}{T_{TES_h} - T_g} = 0.5 \cdot \frac{333K}{333K - 283K} = 3.33$, where T_g is the ground temperature and T_{TES_h} the temperature of the heating system.

Further, $\eta_{grid} = 0.93$ is the transmission efficiency of the centralized grid affecting the electricity imports from centralized PV and CCGT power plants.

Figure 28: Excerpt on the updated conversion technology data, taken from [12]. For more details and respective list of references please refer to the original document.

Table 8: Supply data regarding the energy import and export options for the energy hubs.

Grid Data	Energy Carrier	*Comment*	$fees_{grid}$	$c_{import,j}(t)$ or $v_{export,j}(t)$ [CHF/kWh]	$CO_{2eq,op,vari,j}$ $[g/kWh]$
g-grid$_{local}$	BG; NG*	Import for GBs/CHPPs	$2.20 \cdot 12 \frac{CHF}{kW_{gas} \cdot year}$ [62]	0.138 (BG); 0.082 (NG)[62]	130 (BG)[63]; 208.4 (NG*)[62][8]
e-grid$_{dis}$	Electricity	Import from Trad. e-grid		0.1748 (low); 0.2378 (high)[65]	40 [36]
e-grid$_{chr}$	Electricity	Export to Trad. e-grid		0.062 (low); 0.083 (high) [66]	0.0001[9]
e-grid$_{CCGT.}$	Electricity	Import from CCGT	$7.50 \cdot 12 \frac{CHF}{year}$ [64]	0.2073 (low); 0.2413 (high)[60] [10]	$380[59]/\eta_{grid}$
e-grid$_{Cen. PV}$	Electricity	Import from Cen. PV		0.093 (low); 0.127 (high)[65][11]	$50[59]^{12}/\eta_{grid}$
e-grid$_{cur.}$	Electricity	Local Curtailment	*0*	*0*	*0*
f-grid	Gasoline	Imports to CVs	0	$1.65\ CHF/liter$ [67]	331 [36]
CS-grid	Electricity	Imports from public CSs	$1.60\ CHF/connection$ [36]	$0.584 \frac{CHF}{kWh} \cdot \eta_{pCS}$ [36]	$40 / \eta_{pCS}$[13] [36]

The energy and grid cost charged by the utility company vary with time in a time-of-use (TOU) tariff scheme with high and low tariff hours. The high tariff hours are Mondays-Fridays from 7am – 8pm and Saturdays from 7am – 1pm.

Grid-feed in shall be preferred over local curtailment of excess electricity even under purely ecological objectives, hence an emission credit incentives the export to the grid. The numerical value of the emission credit, ec_{GFI}, is 0.0001 kg/kWh_{el}.

Figure 29: Excerpt on the updated supply grid data, taken from [12]. For more details and information on the indicated references please refer to the original document.

3.4.5 Average building types

In the following, 5 building types were investigated, ranging from small to larger buildings. These represent the average SFH ($SFH\ avg$), the average residential building ($ALL\ avg$), the average MFH ($MFH\ avg$), the average of the largest four MFHs from the subsample of 83 buildings in the City of St. Gallen ($Dwe4\ avg$), and the sum of the largest four MFHs from the subsample of 83 buildings in the City of St. Gallen ($Dwe4\ sum$), investigated in [10]. Their energy demands for stationary and mobile services

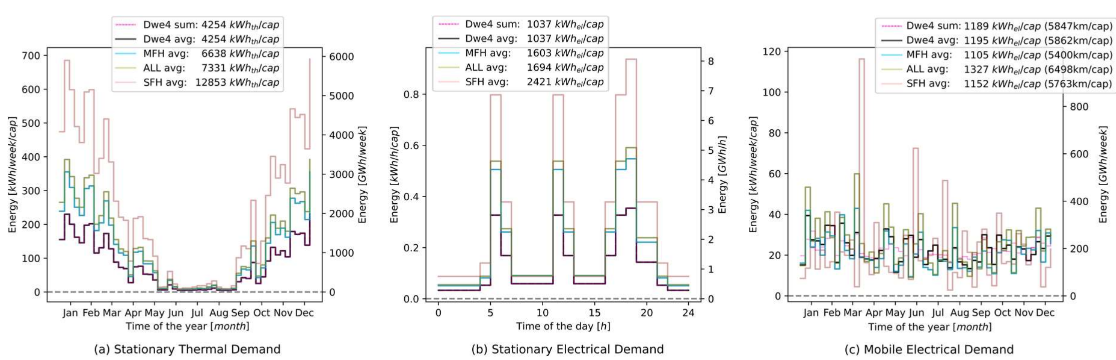


Figure 30: Energy demand of 5 building types for stationary heat and electricity and e-mobility. Taken from [12].

is given in Figure 30. The heating demand follows a seasonal pattern, whereas the stationary electrical demand repeated throughout the year and the electricity demand for vehicles is highly stochastic but shows slight increases, e.g. in winter months, when the ambient temperatures are low.

3.4.6 Cost-Emission Trade-offs under limited existing electricity supply

Figure 31 show the KPI of the optimizations for 5 building types, 5 electricity supply scenarios along the cost-emission trade-offs as well as KPI from the reference cases (ref) comprising conventional technologies. Clearly, the availability of electricity from the traditional electrical grid has a large influence on the KPI of the solutions. The more electricity is available, the lower emissions and cost can be achieved. The benefit of electrification is however reduced with a reduced availability of the centralized, traditional grid. Particularly smaller buildings suffer more from the shortage of traditional supply, so much so that grid-disconnected cases (non) emit more emissions and are more expensive than the reference technology. For the other buildings, grid-disconnected systems are mostly expensive, but they do offer lower emission levels. Under partially limited electricity supply, solutions that emit significantly less than the reference systems, while having identical cost, are common. These solutions should be considered cost-effective climate change mitigation options. A further reduction of emission from the point of zero abatement cost is costly and yields only small additional emission reductions. Climate change mitigation in other sectors might be more cost effective and should be explored.

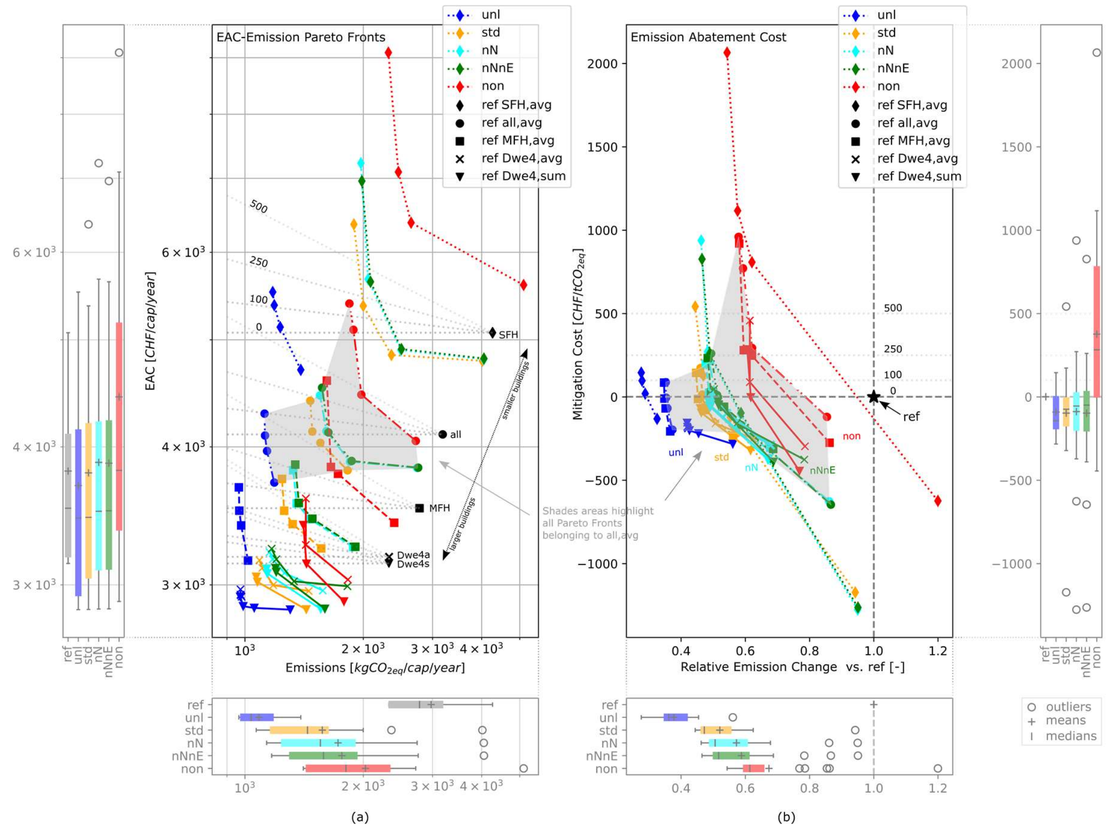


Figure 31: EAC-Emission trade-off results from optimizations. (a) Cost-Emission pareto fronts, (b) emission abatement cost. Taken from [12].

3.4.7 Optimal Energy Flows

Looking at the energy flows by asset type for heat generation (subplot (a)) and electricity generation (subplot (b)) in Figure 32, it becomes clear that decentralized CHPPs are part of the optimal energy system when the electricity supply from the traditional grid is not unlimited and when either emission reduction is sought after or the supply buildings are large. For the case of larger buildings, CHPPs become increasingly cheap in terms of specific cost and can offer an economic way to supply the energy hubs with final energy. For emission-aware settings, the biogas-based systems are prevalent and supply a part of the demanded thermal and electrical energy to the buildings. For smaller buildings boiler-based heating systems are cheaper. In any case, the majority of heat supply is done by heat pumps.

Also, in terms of electrical supply, the CHPPs – when installed – take on a supplementary role as one part of the puzzle to supply electricity to the demand sites. Clearly, the local PV systems provide the majority of electricity to the buildings. The V2G/V2H, i.e. discharging from the EVs to the energy hubs, and the electrical grid - when permitted – are used to supply electricity to the hubs. Depending on the desired emission level, CCGTs or centralized PV systems supply the remaining electricity demand.

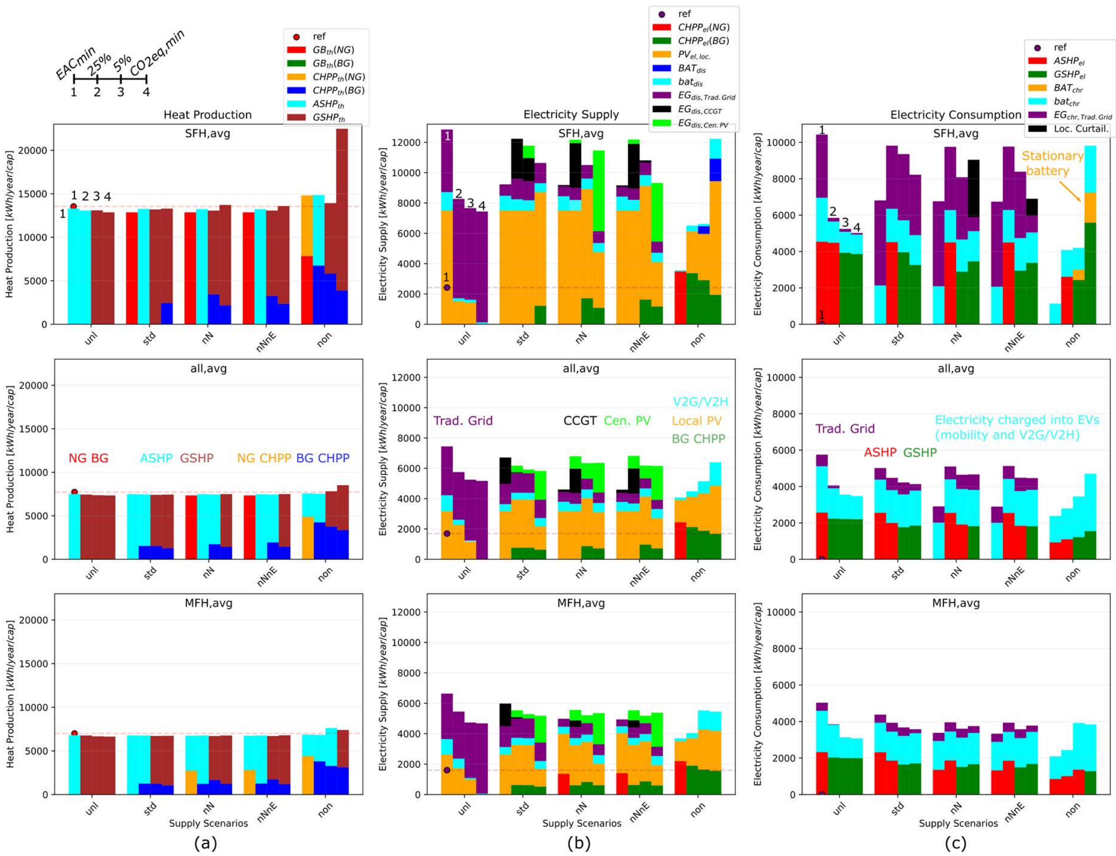


Figure 32: Overview of energy flows by asset type for (a) Heat Supply, (b) Electricity Supply, (c) Electricity Consumption. Taken from [12]. NG = Natural Gas, BG = Biogas

On the side of electrical consumption, heat pumps and EVs are the main assets demanding electricity. For large buildings, in which the specific importance of heating per person decreases, the importance of EVs as an electricity demander is comparable to the demand from the heat pumps. For small buildings, the export of electricity to the grid is significant, but then reduces with increasing building size and number of EVs present at the demand site. Local curtailment of electricity is not typically done and the installation of stationary batteries is also only attractive for extreme emission reduction goals, for small buildings in situations with limited centralized grid capacity. The large number of EVs and hence large amount of mobile battery storage temporally available at the demand sites otherwise are adequate.

3.4.8 Operational Characteristics

Figure 33 summarizes the operational characteristics and optimal design capacities of the optimally selected, designed and operated converter assets at the hubs for all building types, supply scenarios and emission reduction ambitions.
GBs are installed relatively seldomly and often operate at part load, hence the large discrepancy between full-load-hours ($flhs$) and operating hours ($ophs$).

CHPPs are installed in increasing capacities with increasingly restricted centralized electricity supply. Further, CHPPs are used as base load technologies, indicated by the similarity of their $flhs$ and $ophs$ and their high annual operation hours. In cases that focus on emission reductions, biogas rather than natural gas powered CHPPs are used ideally. These are also operated during less hours of the year. Only in the case of no centralized electricity supply (non) CHPPs are even larger and are also used to a larger extent in part load operation.

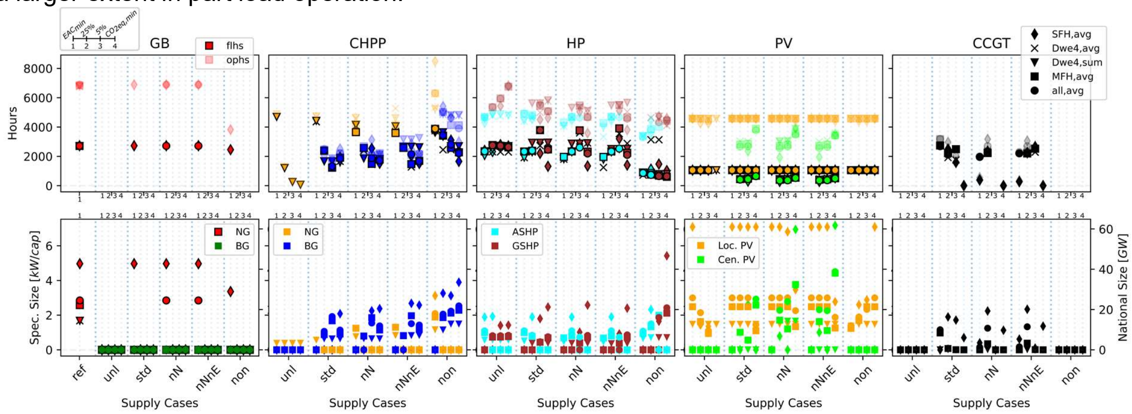


Figure 33: Operational characteristics of the centrally and decentrally installed converter assets. Taken from [12].

Heat pumps are typically operated during many hours of the year but run largely in part load operation. In the case of non supply, the operation of heat pumps is reduced.

PV systems are the backbone of the electricity generation at the demand site, which reach high installed capacities, but due to the availability and intensity of the sun on the panel naturally only reach low full hours of around 1000 h/year. The installation of centralized PV systems is sparser but can add significant solar generation power to the overall energy systems under partially limited electricity supply when emission reductions are sought after. Due to the local oversupply of electricity in summer, the electricity generated from centralized PV in summer is not imported to the end users but rather curtailed. Hence the operational hours as well as the full load hours are reduced due to the curtailment of the centralized PV generation. This circumstance that PV systems produce the majority of their electricity in summer and not in winter limits the usefulness of increasing PV installation sizes beyond the identified installation sizes.

CCGTs are installed and operated only in partially limited electricity supply scenarios and for low-cost objectives. When running, CGGTs are operated close to their name plate capacity and deliver power during 2000 to 2500 h per year.

3.4.9 Energy Import / Export Dependency

The installation and subsequent operation of all these assets requires exchange of energy with the upstream energy supply grids, name the electrical and the gas grids. In most cases, the demand for natural gas and biogas – be it the local demand or the demand of gas for the CCGTs - is significantly lower in the optimized energy hub cases than in the reference (ref) case (see Figure 34a). Even in case of non centralized electricity supply, the optimal energy hubs mostly consume less gas than the reference cases. From the plots on the gas demand, the importance of modelling the centrally available electricity becomes abundantly clear, as the optimal gas demand varies between zero to levels similar and above today's reference values. Further, the ambition to reduce emissions, has significant impact on the gas demand in the optimal solutions.

The role of modelling the limited availability of the existing electricity demand is also clear from the optimal electricity imports to the energy hubs, as there is a strong anti-correlation between the optimal gas imports and the optimal electricity imports. Interestingly, the electricity import demands vary vastly and may take on values much larger but also much smaller than today's reference electricity imports depending on the desired emission reduction goal. Electricity imports from CCGTs are high for low-cost objectives but vanish towards stricter emission targets. Low emission targets show high dependence on centralized PV system, but curtail large amounts of electricity from this source.

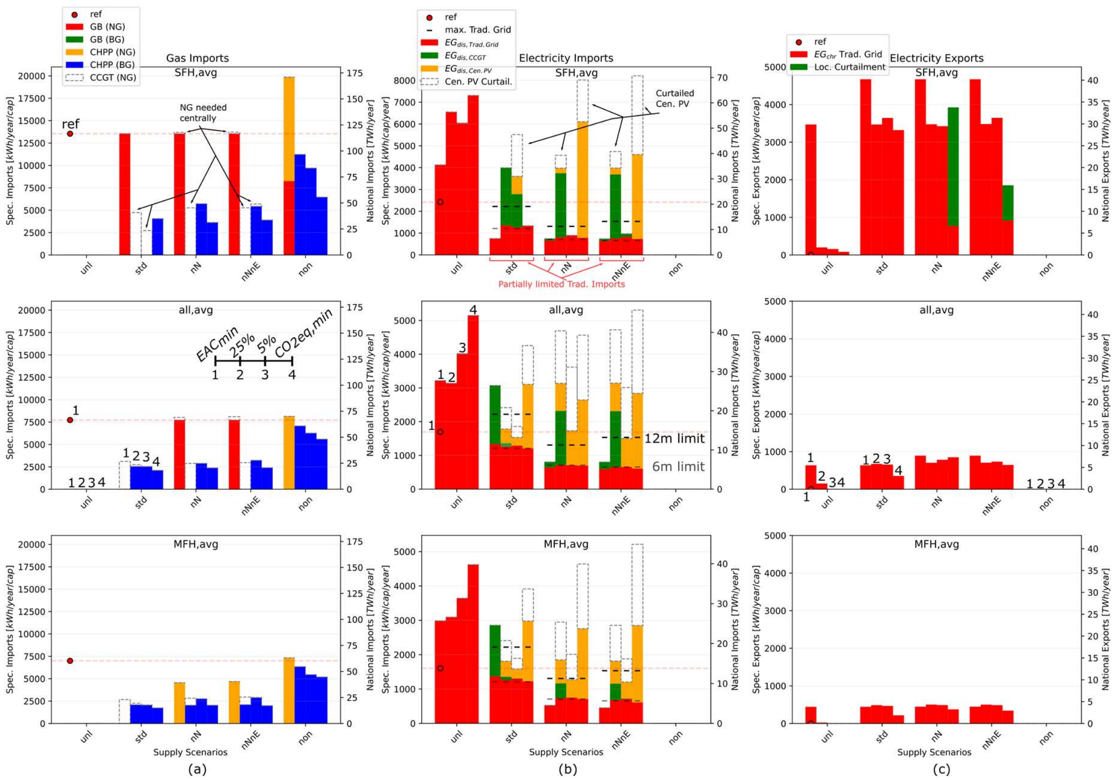


Figure 34: Energy imports and exports arising from the optimal installation and operation of the centralized and decentralized assets supplying the residential energy hub. Taken from [12].

Further, the annual electricity imports from the traditional electricity grid (see red bars in Figure 34b) amount to approximately the amount that is permitted to be cumulatively imported during the six winter months (6m limit) defined by the partially limited electricity supply scenarios. A closer analysis will be performed in Section 3.4.10.

Lastly, the export of electricity to the grid, as a function of the emission reduction ambition, is largely dependent on the centralized electricity supply scenario. While the unl case reduced its grid feed-in for stricter emission mitigation targets down to zero, the partially limited supply scenarios are far from exporting no electricity. For the average residential building (all, avg) the exports of electricity are in the order of the electricity import from the traditional electricity grid. For smaller buildings (SFH, avg) in which the relative size of PV systems is much larger, the amount of exports to the grid is higher than the reference consumption.

3.4.10 Electrical grid limitations

To understand why the modelling of limitations on the existing electrical system has such a large impact on the solutions, we investigate which limitations and by how much are affected in the optimized solutions. As discussed previously, there are three limitations to the supply of the electricity hub from

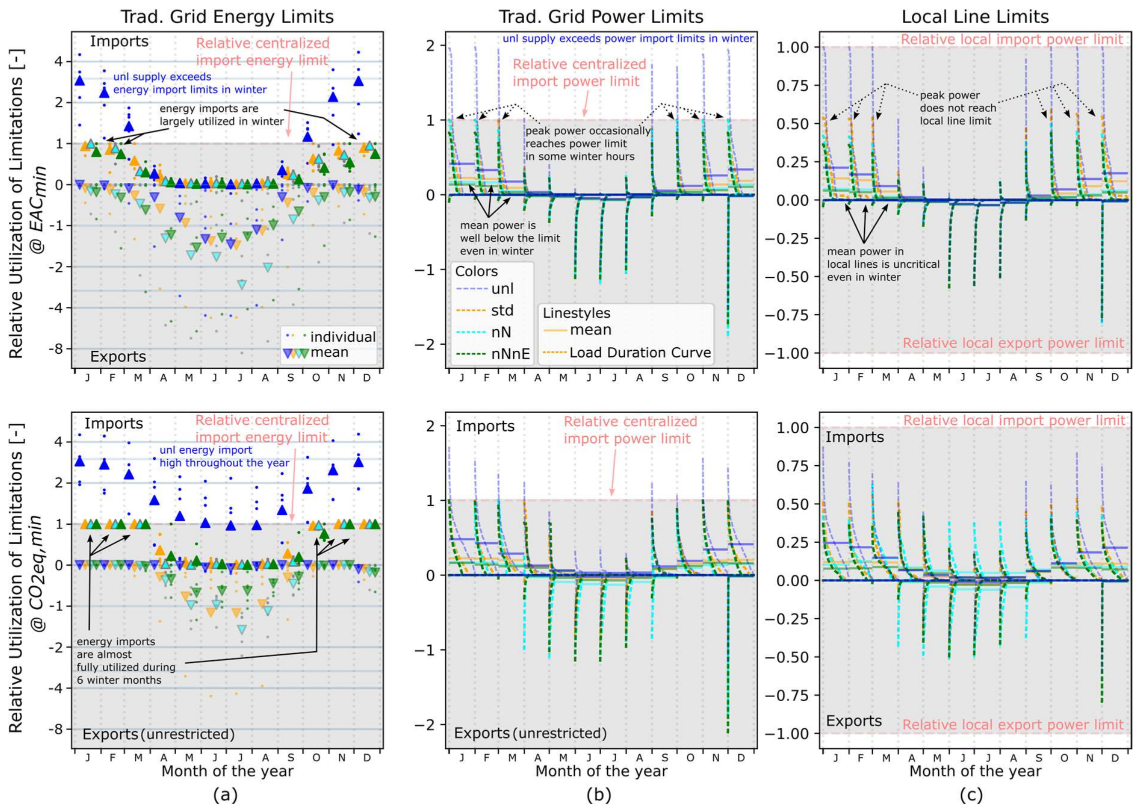


Figure 35: Limitations of the electrical supply from the centralized electricity system to the energy hubs given as individual and mean values over the five investigated building types for two emission reduction targets (top: EAC_{min}, bottom: $CO_{2e\ ,min}$). The areas of permittable energy, power and line draw are highlighted. Taken from [12].

the centralized system: a) energy limitations of the existing assets, b) power generation limitations of the existing assets, c) power limitations due to the local line limits connecting the centralized system with the local energy hubs. The utilization of these limits is shown in Figure 35, where a utilization of 100% means the system is operating at the defined limit[6]. Purely for comparisons sake, the utilization ratios of the unl supply scenario are normalized to the standard std limitations in subplots (a) and (b) despite the unl case not being restricted by these two limits. Subplots (a) displays the monthly utilization for the limits defined by the energy supply capability of the existing e-grid. Focusing on the lower plots, the limit of electricity imports is exhausted during the six winter months, in all partially limited scenarios (std, nN, $nNnE$). During the summer months, however, the imports to the energy hubs collapse to zero in these supply scenarios, indicating a complete shift in importing strategy. The building types in the unlimited unl supply cases import up to three times more electricity in the coldest winter months on average than the loosest limit std permits. This signalizes that the electricity import limitation defined in the partially limited supply cases is active during the winter months but is inactive during summer, where the large exports but literally no imports happen.

In subplot (b) the limitations on the power handling capability of the existing upstream electricity system are tested. The results show that the maximal power draw reaches the power handling capability for few

[6] Note that the local line limits (subplot (c)) re active for all supply scenarios, including the unl scenario.

hours for the partially limited supply cases. For most of the year the power demands are however well below the critical value and typically only use 50% of the maximum power and less on average. Since the import of electricity approaches zero in summer, also the load on the upstream electricity system is very low. Again, in the unl case the maximum power draw surpasses the power handling capacity of the std case by up to a factor of two, indicating that the optimal energy hub system would draw more power than available in today's system if no restrictions are placed on the power draw.

With respect to the local line limits, all supply scenarios (including unl, excluding non) must abide by the same power handling restrictions defined by the local connection power of the buildings to the distribution grid. This connection power is a function of the building size defined by [19], as in [10]. From the subplot (c) it is clear that the local line limit is the least restrictive limitation to the exchange of electricity with the centralized grid.

It is hence important to consider the supply limitations of the centralized electricity system beyond the local line limits, with electrical energy supply limitations being the most restrictive limitation for the investigated systems.

3.4.11 Emission Breakdown

Naturally, the breakdown of emissions is a major concern, which can inform stakeholders on the relative emission importance of the individual contributing factors. Figure 36 displays these emission breakdowns. In comparison to the reference case, the overall emissions are largely reduced when switching from conventional (ref) energy technologies to hub technologies under unlimited (unl) centralized electricity supply. This is largely related to very significant reductions in operational emissions due to avoidance of gasoline to propel private cars and the avoidance of natural gas to heat the buildings. To some extent installation and purchase of the necessary equipment to enable these solutions eats up the emission savings by introducing more embodied emissions due to larger embodied emissions from electric vehicles and more complex stationary technologies. Nevertheless, the overall emissions drop to 25-35% of the ref value.

With the modelling of the limited electrical supply, the emission savings are not as dramatic, as the limitation to clean electricity supply, requires alternative, less emission-friendly solutions to cover the residential demands. In cases where natural gas is used to operate the same gas burners as in the ref case (cf. also Figure 34), the stationary operational emissions stay largely untouched. If CHPPs are however installed and burn natural gas, as in the minimal cost solutions of the larger buildings, the emission contribution from burning natural gas can decrease significantly. Even larger emission reductions are possible when switching from natural gas to biogas.

Interestingly, biogas based CHPPs are part of all $CO_{2eq,min}$ solutions and can help to significantly reduce the emissions over the ref case. Therefore, under these circumstances the supply of sufficient amounts of clean biogas is essential for emission mitigation under restricted electricity supply and should be a priority. Nevertheless, the biogas-based heat and power generation is virtually the only contributor to operational emissions in these cases. If alternatives of cleaner, equally- or even more affordable fuels were available, this contribution could further sink in future.

Lastly, another large portion of the total emission stems from the embodied emissions of the battery electric vehicles. Research should be advanced to decrease their environmental burden to increase the benefits of electrification.

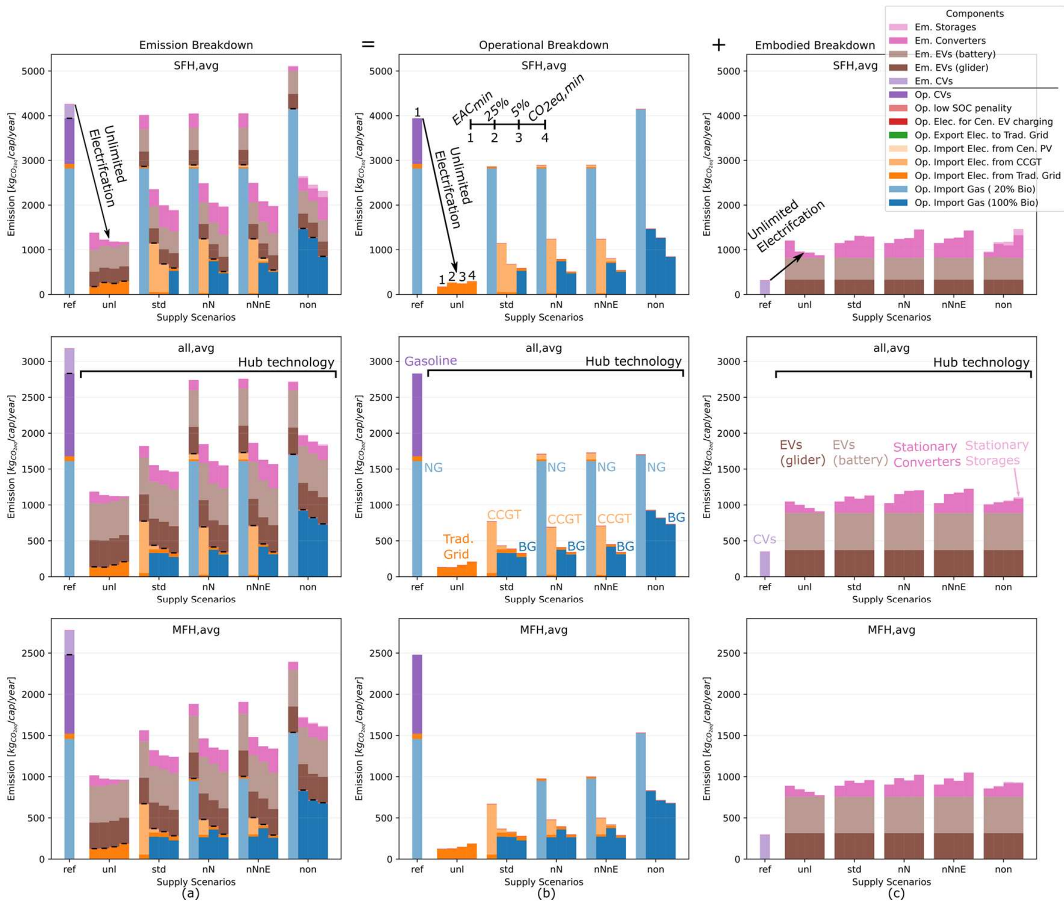


Figure 36: Emission breakdown of the optimal energy systems. for 3 exemplary building sizes, 6 supply scenarios as total emissions (a), operational emissions (b) and embodied emissions (c). Taken from [12].

3.4.12 Cost Breakdown

Equally interesting is the breakdown of cost. Figure 37 gives an overview of the individual cost components and their share of the total cost. Revenues from the sales of electricity to the grid are plotted on the negative y-axis and must be subtracted from the positive axis to obtain the total cost. With the shift away from the basic technologies (ref) to the multitude of technologies installed in the hub solutions comes a shift away from operational cost to one-off cost. The one-off cost include the cost for purchasing the equipment (stationary and mobile), as well as replacing assets along the project horizon and the revenue (negative cost) from salvaging the remaining values at the end of the lifetime. Similar to the emission breakdown, the cost of EVs contribute substantially to the total cost. Further, in smaller buildings, where the specific cost of the stationary equipment is higher and also the specific energy demands are higher, the stationary systems also contribute large shares towards the total cost. In larger buildings the cost contribution from stationary assets is relaxed.

As seen previously, the assumption of limited electricity supply, changes the optimal portfolio of technologies installed and operated to satisfy the residential needs cf. the unl case.

Particularly when natural gas (with 20% biogas share) is used in minimal-cost solutions, the cost of this gas is the main contributor to the operational cost of the solutions. For minimal-emission solutions pure

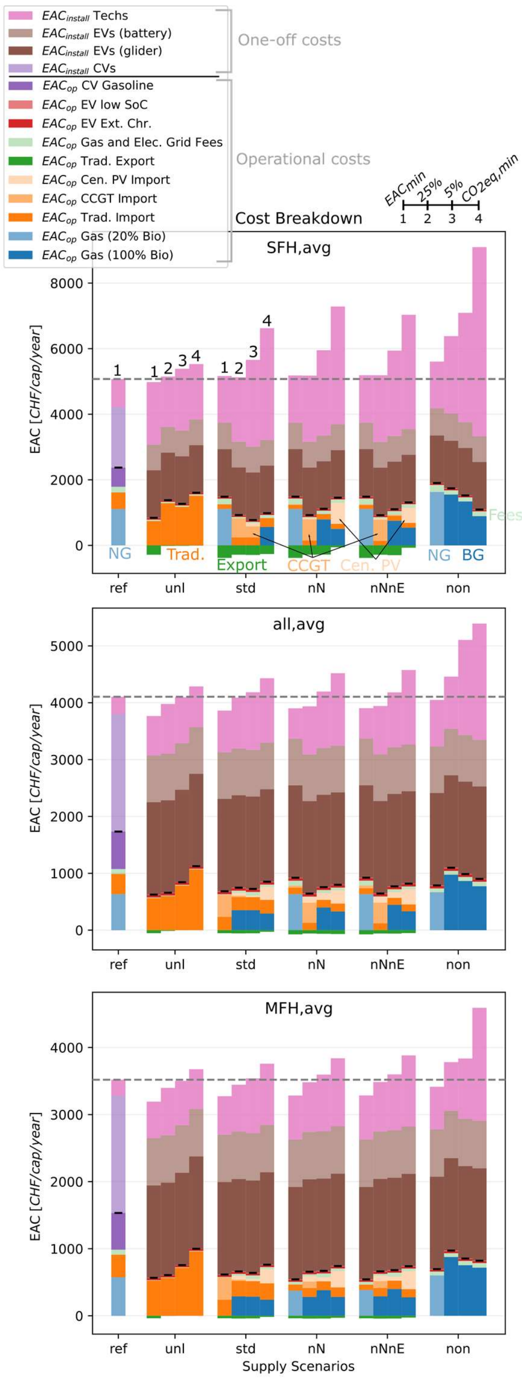


Figure 37: Cost Breakdown of the optimal energy systems for 6 supply scenarios, 3 exemplary building types and different emission reduction targets. Taken from [12].

biogas is used as a means to operate the CHPPs. The biogas usage however is reduced and not the sole contributor to the operational cost of the solutions. Instead, cost for biogas are accompanied by cost for the import of electricity from the centralized e-grid – if allowed – and cost for the import of centralized PV electricity. Since the centralized PV panels have no operational cost themselves, these costs are entirely related to the cost of supplying the cen. PV electricity to the consumers, i.e. grid connection cost. Grid access fees however play a minor role.

3.4.13 Impacts of the upstream grid

Certainly, the bottom-up decisions made on the local scale to optimally supply the residential energy demand causes changes in the utilization of the energy grids. Hence, the upstream operators and suppliers of these grids will be impacted by these changes, if they were to roll out on a large scale. Figure 38 summarizes these changes from the perspective of upstream supply agents in absolute and relative terms based on a single building type: the average of all residential buildings (all, avg).

Subplot (a) shows that the revenue stream of a utility company that sells natural/biogas as well as electricity from centralized supply systems to consumers will lose up to 50% of its income stream. This is largely related to the drop in revenue from gas sales, which the possibly increase sales of electricity cannot compensate appropriately. This is even the case although the utility company has gained an additional energy demand sector to supply: the demand for electricity due to the electrification of vehicles. In terms of absolute quantities, the utility company can expect to lose between CHF 200 and CHF 450 per average residential building per year.

Additionally, a sensitivity of these results to a changing Feed-in-Tariff (FiT) was studied, which the utility company may implement to avert the revenue loss by paying the prosumers less for their grid feed-ins. Next to the standard FiT with a year-round high/low tariff remuneration, two other $FiTs$ were tested: $nSFiT$, does not remunerate grid exports from prosumer in the six summer month, while $nFiT$ does not offer any compensation for grid feed-ins. As can be seen from subplot (a), the impact of altering the Feed-in-Tarif is

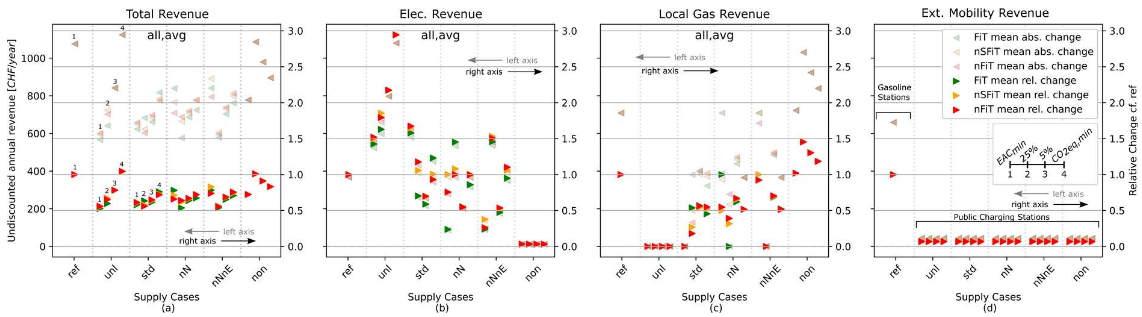


Figure 38: Changes to the revenue stream of upstream energy entities due to the local bottom-up decision making for a single building type: average of all residential buildings (all, avg). Total revenue does not include the revenue from gasoline sales, as this is assumed to profit another business. Taken from [12].

minimal, if the energy hub solutions boast such high flexibility and can hence alter their asset design and operation to increase their own benefit, assuming that they are aware of these tariff changes.

3.4.14 Intermediate Conclusions

Electrification of residential energy systems and vehicles has major advantages in terms of cost-effective emission mitigation. Substantial emission reductions of more than 60% can be achieved at zero additional cost. If however insufficient clean electricity is available, electrification and hence decarbonization becomes more challenging requiring the interplay of a multitude of technologies to optimally interact enabling the supply of energy and power at low emission levels and low cost.

Particularly the supply of electrical energy in winter is a problem to electrification since the demand for energy in winter is higher than during summer - not least because of the proliferation of heat pumps and seasonally impacted EVs - and the supply capacities are limited in winter due to natural circumstances of the hydrological cycle in Switzerland and potentially restricted electricity exchange with the neighbouring countries.

Depending on the desired level of emission mitigation and willingness / acceptance to pay for this emission mitigation, various and different solutions to provide residents and their mobility exist. These solutions are complex solutions interlinking many supply technologies to optimally reap the benefits of each and every one of them. These solutions, however, do not reach the emission and cost levels possible under the assumption that the electrical grid is abundantly available at its current quality and emission-intensity, but only see average emission mitigation of approximately 50% at zero additional cost.

In contrast to unlimited scenarios, under (partially) limited centralized electricity supply, biogas driven CHPPs become a core technology to supply residential stationary and mobile energy demands, which ideally operate in combination with local PV and V2H/V2G systems as well as heat pumps. While CCGT and ASHP including solutions are economical but relatively polluting, solutions including GSHPs and vast amounts of centralized PV are ecological but expensive, also despite and because of large curtailments of centralized PV in summer. Trade-off solutions offering intermediate levels of emission mitigation are hence advisable.

Due to the emission-intensity of the required energy carriers, but more due to the embodied emissions of all energy and mobility assets, the emissions levels do not approach zero emissions. Hence, to further advance the emission mitigation effectively, it should be a priority to make more clean electricity or alternative fuels available, to reduce embodied emissions from vehicles but also from stationary assets and to address the problem of seasonality, with high electrical demands but low electrical supply particularly in winter.

4 Conclusions

In conclusion, the DisCREET project investigated the multi-faceted problem of optimally supplying energy to residential energy and mobility demands by optimally planning the installation and operation of suitable technologies from an integrated planning perspective for various demand sites, under various techno-economic conditions and under various centralized electricity supply scenarios. This integrated assessment is extremely important for two reasons: 1) The residential energy and mobility sector are responsible for 40% of Switzerland's annual CO_2 emissions due to their current high reliance on fossil fuels, 2) the related residential energy and private mobility systems are replaced by the thousands daily and typically exhibit long lifetimes of approximately 20 years. Therefore, inappropriate decisions made today thus potentially leads to long-lasting consequences – especially regarding cumulating GHG emissions – for the next 20 years and must be avoided.

Hence, a methodology was developed, in which a wide variety of readily available technologies is computationally modelled and optimized, to identify the solutions that minimize the total cost and the total lifetime CO_{2eq} emissions of such supply problems while respecting techno-economical-ecological limitations. At the core, a number of data sets and associated simulation tools feed data to a central optimization tool, which by the minimization of adequate objective functions enables the holistic assessment of optimal transition pathways to clean, affordable, and reliable, sector-coupled energy and mobility system solutions from the perspective of bottom-up decision makers, e.g. consumers/prosumers, building planners, etc. The developed software is a suitable, expandable and adaptable tool that can answer many specific questions by qualitatively and quantitatively present the competitive and symbiotic relationships of various assets.

The presented analyses show the complexity and depth of knowledge needed to make informed decisions when selecting the best technology to upgrade to. Especially the concept of comparative advantages of technologies requiring a holistic analysis including a wide variety of assets, the multi-objective perspective defining the desired outcomes and actors as well as the importance of external boundary conditions were highlighted to be critical when analysing such optimal system transformations.

Focusing on identifying actionable pathways for economical GHG emission mitigation in the residential sector, overall, electrification of the supply systems including the vehicles is identified as highly advisable in Switzerland of today. It should hence be accelerated as much as possible for stationary as well as mobile assets. Local PV systems and heat pumps as well as electric vehicles form the solid foundation of this electrification process that brings along large emission and notable cost reductions by replacing conventional boiler-based heating systems and conventional combustion vehicles. With special attention to co-generation plants, the analyses found that natural gas-based co-generation can present economical solution for large demand sites, however, if enough electricity is available centrally and GHG emission mitigation is valued over inexpensive energy supply, CHPPs get displaced by electrical supply from the grid in combination with more ecological heat pumps.

Despite its great advantages, the discussed electrification of residential heating and vehicles systems brings along some unintended consequences like higher upfront cost, more complex solutions due to higher asset counts, and – maybe most importantly – a shift in energy carrier demand. This shift replaces high seasonal gas demand with high seasonal electricity demand, plannable electricity supply with intermittent electricity supply and unidirectional with bi-directional electricity supply. Due to the large operational flexibilities of heat pumps and electric vehicles in combination with smart local demand response, this is a solvable problem for short-term fluctuations. However, long-term, i.e. seasonal, energy supply and demand mismatches cannot be handled by these means but must be addressed by alternative electricity supply systems that can provide electricity particularly in winter.

Since the existing centralized electricity supply system in any country, but particularly in Switzerland due to its high reliance on hydro power, is limited in its ability to supply electricity throughout the year and may foreseeably be further restricted due to the planned phase out of nuclear power and a desire to reduce the import dependency from neighbouring countries, new electricity generation installations are needed to supply the desirable electrification. These new installations can comprise centralized and/or decentralized installations. Centralized PV systems and centralized CCGTs are tested alongside decentralized systems, including gas-based co-generation in combined heat and power plants (CHPPs).

Under various limited centralized electricity supply scenarios, the optimization results show that decentralized co-generation presents itself as a fundamental part of the optimal energy supply for residential energy and mobility. Displaced by more economical CCGTs in cost-driven scenarios, the biogas driven CHPP systems work alongside and in synergy with the other decentralized assets in solutions involving intermediate trade-offs between cost- and emission-performance, and are joined by extremely large centralized PV systems for objectives of lowest GHG emission levels.

Further, natural gas driven CHP systems are found to be economical options for residential sites with large energy demand and hence larger optimal system sizes, and for high heating supply temperatures (as heat pumps lose their competitive advantage). Further, CHPPs can be attractive for optimal ratios of heating to electricity demand at the load sites. This ratio is influenced by the number of EVs present at the load site. This is true even under an assumed unlimited electrical supply from the existing electricity supply system.

In the contrary case of isolation from the centralized electricity grid (no existing nor new centralized installations), CHPPs work in synergy with local PV systems to supply the sites' desired electricity. And although ecologically less favourable than solutions with grid-connections, electrification under this isolated bi-asset electricity supply still emits less GHGs when supplying the residential, heating, electrical and e-mobility demands than comparable reference systems operating with conventional boilers and conventional cars. As long as sufficient PV area is available, heat pumps can take over the majority of heating and local CHPPs can supply the remaining heat and especially electricity in winter. An additional switch to operating the CHPPs with biogas instead of natural gas further reduces the operational emission by roughly a factor of two.

Due to the large pool of available energy conversion and storage assets, and the inherent flexibility to operate the assets to their specific advantages, residential electrification is thus recommendable independent of the centralized electricity supply situation. In case sufficient clean and affordable electricity is available from the centralized grid, the largest emission reductions are expected. In case insufficient clean and affordable electricity is available from the grid optimally designed local energy systems can provide viable supply alternatives.

To enable these solutions some barriers to implementation must however be overcome. These include the higher upfront cost, higher complexity in system integration and installation, the handling of larger and bi-directional seasonal variations in the electricity supply, and the supply of sufficient amounts of biogas must be ensured for the operation of eco-friendly co-generation plants. These biogas demands exceed today's supply by far, amounting to approximately 30% of today's natural gas consumption. An expansion of the availability of biogas is hence sorely needed.

Moreover, the investigations highlight the following potentials for further GHG emission reductions in the residential sector. If possible in a reliable and affordable manner, the amount of clean, centrally available electricity should be increased, e.g. by expansion of current hydro power generation. Since the use of biogas is not emission-free due to the emissions related to its upstream supply improvements related to the lowering of these emissions including the potential supply of eco-friendly synthetic drop-in fuels could be largely beneficial, if they can be provided at affordable prices and in large enough quantities.

Further, since the embodied emissions of EVs – and in particular the batteries of EVs – make up a remarkable proportion of the overall annualized emissions, research on less polluting battery production is suggested. Alternatively, studies on the impact of smaller EV batteries could be conducted.

Summarizing, DisCREET presents an opportunity to study the effects of optimal decision making regarding stationary and mobile asset design and operation on a local level under varying internal and boundary conditions. The developed method thereby facilitates the holistic, structured, and detailed assessment of complex multi-energy system relationships to identify desirable and unintended consequences of upgrades energy systems. In particular, the tool was used to investigate the effects that the availability of technology and the advent of electro-mobility and heating electrification has on residential energy supply. This was demonstrated to be possible for a wide range of residential building sizes, from single buildings to complete building districts. The integrated assessment of vehicle and stationary asset design and operation is a unique characteristic of the tool, because of its capability to select optimal components designs within a continuous bandwidth. The overall strong dependence of the optimal result on the applied CO_2 mitigation goal begs the societal questions how much each building ought to contribute to mitigating climate change, what acceptable CO_2 mitigation cost are and how the upgrade to sustainable, yet affordable energy solutions can be accelerated.

Private house owners, building developers, grid operators and utility companies should be equally interested in how the techno-economic conditions affect the ideal choice of technologies and operational strategies which will largely define the cost, emissions, operational patterns and in turn the infrastructure utilization in future energy systems. Since the decisions of today will lock-in our usage patterns for the next years if not decades, we should boost the utilization of the above described and similar data-driven optimization tools for the strategic planning of energy transitions around the world.

5 Outlook and next steps

The presented data, methodology, results and analyses are a starting point for future research on planning the optimal energy transition at the interface of stationary and mobile assets from a holistic perspective considering the overarching energy trilemma of energy affordability, sustainability and security. Clearly, the analyses become more interesting and enlightening, when more system aspects, technologies and conditions are incorporated, so that a comprehensive understanding of the interaction between the individual system components can be generated.

Fortunately, the presented data as well as the developed methodology is easily adaptable and expandable for future research endeavours. In particular, it would be interesting to

- Conduct more sensitivity studies on energy and asset prices as well as conversion efficiencies, e.g. to investigate the effects of anticipated improvements for battery and renewable energy technologies or to investigate the effect of regional differences on the optimal systems.
- Further address the identified problem of seasonality.
  - The inclusion of seasonal storage technologies, such as power-to-gas could alleviate the situation.
  - Incorporation of renewable energy technologies that are particularly well suited to supply electricity in winter, such as façade or alpine PV systems and/or wind turbines, even if installed abroad and thus subject to import restrictions, cost and losses.
- Investigate the transformational changes to the utility / upstream agents more closely to identify mutual benefits for a win-win energy system transformation to accelerate the desired changes towards reliable, low-cost, low emission energy and mobility systems.
- Examine the potential changes in optimal residential energy system design and operations due to
  - Direct interaction with dynamic energy markets rather than static utility-driven conditions.
  - Access to other energy markets, like control / backup power markets additionally incentivizing flexibility.
  - Diverging strategies of centralized supply expansions via tighter integration with the European Union and its energy supply capabilities.
  - Endogenous coupling with top-down energy system models.

Importantly, the conclusions and insights in this work should inform policy making and find their way into application in the field.

6 National and International Cooperation

On a national level, various cooperations were part of this project. A working group involved parties from the utility of the City of St. Gallen (Stadtwerke Stadt St. Gallen), Energie 360°, IWK, Federal Office of Energy (BFE). Parts of the methodologies and results were co-developed with the Dr. James Allan from EMPA (building energy demand) and Dr. Giacomo Pareschi (mobility demand) from ETH Zurich.

There were no international cooperations in this project.

The authors of the report are immensely thankful to the abovementioned parties and individuals for their continued support, thoughtful inputs and interesting questions that arose during and outside of the project meetings.

7 Communications

This report serves as one of the main communications of the work. Alongside two publications, specified in Section 8, are the basis supporting the work presented in this report. Multiple, regular milestone meetings were held internally with the working group. A final such meeting was held in December 2021. In February 2022 a public communication event was conducted. The summary of the Dissemination Event is stated below.

Institute of Energy Technology

Aerothermochemistry and Combustion
Systems Laboratory
Prof. em. Konstantinos Boulouchos

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Report on the Dissemination Webinar of the DisCREET Project on February 28th, 2022 titled

«Kostenoptimale Dekarbonisierung UND Versorgungssicherheit für Wohngebäude und individuelle Mobilität: Welchen Beitrag können dezentrale Anlagen leisten?»

Summary

1. Introduction

The webinar has been organized by the Aerothermochemistry and Combustion Systems Laboratory (LAV) of ETH Zurich, of which the Energy Systems Group has been responsible for carrying out the *DisCREET* project, which has been funded by the Swiss Office of Energy (SFOE) and supported by a project group composed of several stakeholders (Carina Alles & Stephan Renz from SFOE, Harry Künzle & Fredy Zaugg from the City of St. Gallen, Ingo Siefermann & Stefan Ellenbroek from Energie 360°, Stefan Schaffner from IWK). The webinar should service as dissemination event to the broader community of decentralized energy suppliers, utilities, industrial companies and related government offices. In addition to the scientific presentations in relation to Moritz Mittelviefhaus' dissertation, that has been successfully defended on January 17th, 2022, a talk by the Director of the "St. Galler Stadtwerke" Mr. Marco Letta served as reflection of the research findings from the point of view of a regional energy provider.

2. Presentations

After a short introduction by Professor Konstantinos Boulouchos on the embedment of the present research in the context of the current and foreseeable Swiss energy research landscape, the leader of the Energy Systems Group, Dr. Gil Georges gave an overview of related research efforts at the Aerothermochemistry and Combustion Systems Laboratory (LAV) in the area of decentralized energy supply and the previous related project on biogenic CHP swarms (*CHPSwarm*), which was the predecessor of the current *DisCREET* project.

Thereafter, Moritz Mittelviefhaus presented the most important insights from his research. The complex optimization model that he has developed has been applied to a set of 83 residential buildings, adequately representing about 1% of the total number of residential buildings of the city of St. Gallen.
In a first step it could be shown that the electrification of both buildings' heat with heat pumps and individual motorized mobility with electric vehicles using the help of local PV and (for larger buildings) CHP installations could lead to LCA-based CO_2 reductions of about 65% at equal costs for the private building owners in the case of unlimited availability of centralized electricity supply during times that the necessary electricity generation could not be provided by the local production within the "energy hub" of each building or set of buildings.

In the more realistic case of limited energy and peak power supply from the centralized electricity generation system, already existing centralized supply systems were optimized in combination with newly installed (centralized and decentralized) technologies in order to assess the optimal cost- and CO_2-wise performance of each "energy hub" as well as the design and operation of the energy assets. Therefore, three scenarios of partially limited centralized electricity availability in addition to the aforementioned unlimited external supply case and another extreme "autarky" example - for which no external electricity supply from centralized generation was available - was assumed. While in the autarky case barely any CO_2-advantage at equal costs could be observed, the three partially limited scenarios had a very similar performance with LCA-CO_2 saving being around 50% compared to the reference case under equal costs. The scenario corresponding to the current situation in Switzerland was thereby most beneficial while in the case of no nuclear electricity (one subcase with limited but realistic and one subcase with "prohibited" cross-border electricity imports and exports) have shown only marginally worse performance, still much better than the reference (non-electrified case for heating and passenger cars). The optimal configuration and operation of assets however varies for the three scenarios. In addition to decentralized small-scale and centralized utility scale PV, CCGT powerplants are installed for minimal costs, while biogenic CHPs emerge for minimal CO_2-emissions. The realistic amount of available biogas and centralized PV generation would pose a challenge though.

Finally, in a third step, the influence of future technology and energy carriers (not commercialized or widely applicable yet) on the performance and on the configuration of the decentralized energy system ("energy hub") has been assessed. Three cases with additional sources of electricity generation have been thereby examined: optionally limited or unlimited wind imports from international production sites, availability and acceptance of CCGTs with Carbon Capture and Storage (CCS) and decentralized CHPs fed by imported hydrogen. The results of the new optimization show further CO_2-reductions compared to the second step with an ascending order of CO2-savings from CCGT with CCS through CHPs with H_2 to finally substantial wind imports.

Furthermore, the following points are worth noticing:

a) the results of the optimization and therefore insights obtained are robust against variations of input parameters, b) the decentralized Energy Hubs are substantially less cost and emission intensive per capita with increasing size, c) in all cases the operational CO_2-emissions at equal costs are massively reduced, while the embodied (grey) CO_2-emissions were somewhat higher, leading to the mentioned substantial reductions in LCA-based CO_2-output, d) the very low number of such Energy Hubs in the current market is attributed to the overall complexity of their optimal configuration and the high (upfront) investment costs for the private owner, so that e) a substantial deployment of such, in principle highly beneficial decentralized systems can likely only be achieved if service providers, such as regional energy providers, will be involved which can deal with the complexity/coordinated controls, life-cycle cost optimization and have the capacity to act as intermediaries between the private owner and the (wholesale) centralized electricity suppliers and on the overall energy policy options of the country.

The subsequent presentation by Marco Letta illuminated exactly the position of such a regional utility. Starting from the vision for a zero-CO_2 in St. Gallen in 2050, he provided the most important ingredients for their implementation strategy: Besides a substantial expansion of PV installations and both small and large district heating grids the anticipated doubling of the peak power demand - due to heat pumps and e-mobility of the city - would be met by strategically placed CHPs with a power of several hundred KW to a few MW.

Based on a huge amount of data and the utility's expertise in using them for installations and optimized real-time operation CHPs serve already now the substantial reduction of the necessary grid power and input from outside, thus providing significant economic benefits within the region. In another illustrative example the speaker could demonstrate in a local application the combination of PV and CHPs (certainly to be "CO_2-free" around 2050) has contributed to 85% self-sufficiency of the system over the whole year.

Marco Letta has also announced activities towards a "Real-Laboratory" of such concepts and defined at the end necessary boundary conditions set by the national energy policy in order that such systems can be widely deployed.

Overall, this second talk fully confirmed the practical application of the insights from the *DisCREET* Project (and vice-versa) providing evidence of the usefulness of such optimization tool for guiding future designs of optimized energy hubs.

3. **Discussion in the plenum**

A vivid discussion followed during the Q&A session. Many among the more than 50 attendants have contributed with relevant questions related (indicatively) to useful expansions of the optimization tool to include district heating to enlarge the installations, the potential of methanol and other liquid renewable fuels for the CHPs, the way that CHPs are supposed to operate (power- or heat-demand driven) the issue of noise and pollution (if any) associated with CHPs, the reasons for the impressive CO_2-reduciton at equal costs, the role of digital/IT in this overall context, etc., etc.

Most of the questions have been answered convincingly while others have provided very useful "food-for thought" for further expansion of the work.

4. **Conclusion**

The webinar has been very successful, in that – among others – it has brought together an unexpected high number of participants from the whole community. It has in addition raised the awareness of diverse relevant stakeholders of the benefits and potential of optimized energy hubs (including the usefulness of CHPs with future renewable fuels).

Moreover, it has been confirmed that expansion of the optimization tool despite the closing of LAV would be highly desirable and placement of such future work in an appropriate research group within or outside ETH Zurich needs to be pursued. Finally, a visit of the involved colleagues from ETH/LAV and SFOE to the St. Gallen Stadtwerke with a scope of strengthening the links and define next steps of cooperation based on the needs of the local utility has been envisaged and will be scheduled soon.

Prof. Konstantinos Boulouchos

Dr. Moritz Mittelviefhaus, Dr. Gil Georges

March 7, 2022

Related Links to video recording and slide collection:

- https://www.youtube.com/watch?v=dOKq-a6LZok&t=21s&ab_channel=DisCREETResearchProject
- https://www.aramis.admin.ch/Texte/?ProjectID=40672

8 Publications and Additional Material

[10] peer-reviewed journal publication accepted in *Applied Energy*

[12] peer-reviewed journal publication accepted in *Advances in Applied Energy*

[20] Doctoral Thesis of Moritz Mittelviefhaus

[21] Webinar Recording of the Dissemination Event on Feb. 28th, 2022

[22] Project Repository including Webinar Slide Collection of Webinar on Feb 28th, 2022

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[22] DisCREET Project Repository incl. Slide Collection on Kostenoptimale Dekarbonisierung UND Energieversorgungssicherheit für Wohngebäude und individuelle Mobilität: Welchen Beitrag können dezentrale Anlagen leisten? ARAMIS n.d. https://www.aramis.admin.ch/Texte/?ProjectID=40672 (accessed April 11, 2022).

10 Appendix

In the beginning stages of the project, the optimization tool was developed from the ground up. Intermediate optimizations tested the capabilities of the tool and identified interesting pathways to expand its functionality. Some of the related intermediate results are presented here. Please note that the results presented here are not peer reviewed results and comprise initial sets of supply and demand data, a limited set of objectives and assumptions different from the peer-reviewed results presented in the main section of the report. These results are only intended for the interested reader to highlight other aspects of the analysis and lead through a part of the thought process to arrive at the per-reviewed results of the main sections of this report. The conclusions and insights must therefore be understood in that context.

Between these initial results, presented in the appendix, and the peer reviewed results, presented in the main section of the report, the supply and demand models were updated with more detailed and up-to-date data, the objective function was expanded to include operational emissions and later embodied emissions to be able to optimize along the cost-emission trade-offs and the e-mobility demand model was updated from *plug&charge* over *smart charging* to *V2G/V2H* capable systems to name a fundamental changes to the underlying models.

10.1 Single Building Case Study on Synergies between CHPs and E-Mobility

In an early study, we investigated the impact that electro-mobility has on the optimal design and operation of an energy hub. We also analysed the effect that the availability of a CHP system as an energy conversion device has on that solution. Figure 39 show the overview of the four cases that were studied to examine the four supply/demand combinations.

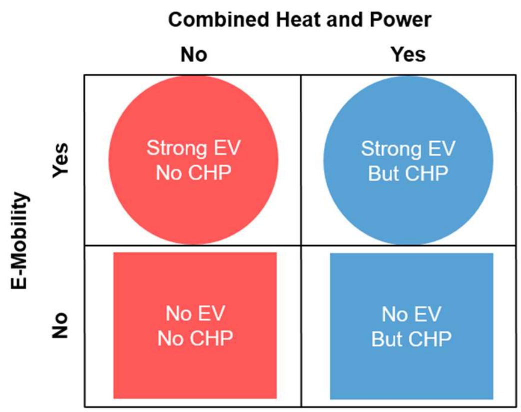

Figure 39: Overview of the four case studies of the first study

10.1.1 Stationary Demand Modelling

A multi-family building constructed in 1977 with 16 dwellers, spread over 6 apartments and a total of 1276 square meters of heated floor area was used as a basis for analysis. The stationary energy demands comprise energy demands for space heating, domestic hot water production, and building-related electricity.

Figure 40 depicts the thermal energy demand profiles over the course of a year. As typical, the space heating energy demand dominates the hot water energy demand, both in terms of maximum load requirement and total yearly amount. Further, space heating energy demand shows a clear temperature-dependent, seasonal trend, whereas the hot water energy demand shows less variation thought the year.

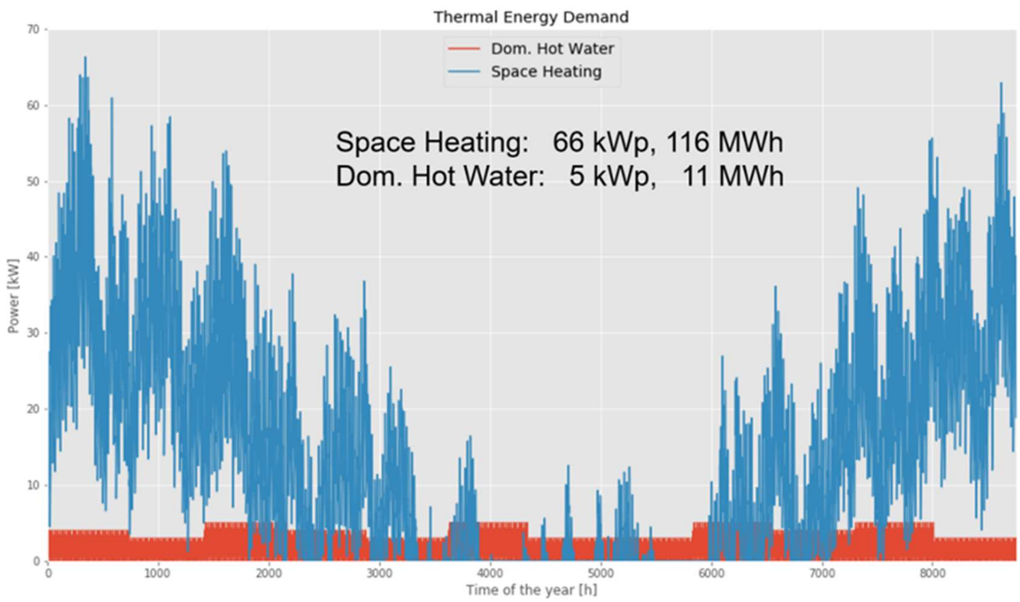

Figure 40: Model of the yearly, hourly-resolved thermal energy demand of the 1977 multi-family building under study.

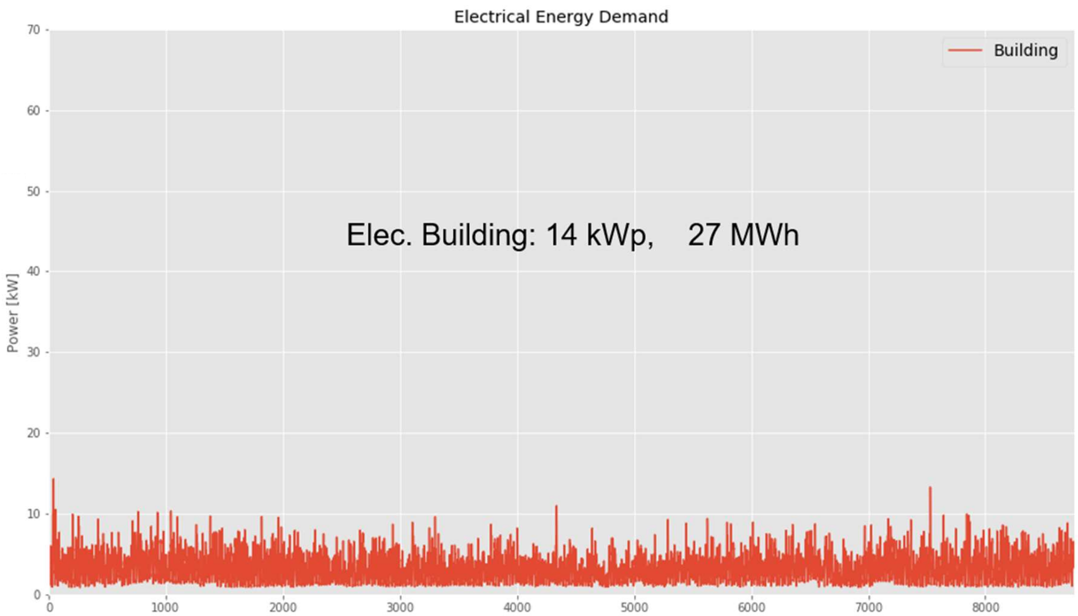

Figure 41: Model of the yearly, hourly-resolved electrical energy demand of the 1977 multi-family building under study.<

Figure 41 illustrates the electricity demand of the dwellers and their stationary activities. One can see the much smaller magnitude of load peaks and the total amount of electricity demanded over the course of a year as compared to the space heating energy demand.

10.1.2 Mobile Demand Modelling

Next to the stationary demand, the dwellers also desire mobility. Therefore, they use, amongst other means of transport, their light duty vehicles. For the analysis we assume that the 16 dwellers in 6 apartments own 9 vehicles. This is estimated based on an average motorization rate of roughly 55% in Switzerland. These vehicles will be assumed either being traditional, internal combustion engine vehicles (ICEVs) or battery electric vehicles (BEVs). In case of BEVs, this will increase the electrical demand from the energy hub since the vehicles are assumed to charge off of the energy hub infrastructure. Contrarily, ICEVs do not affect the design or operation of the hub since they do not create additional demand for heat or electricity.

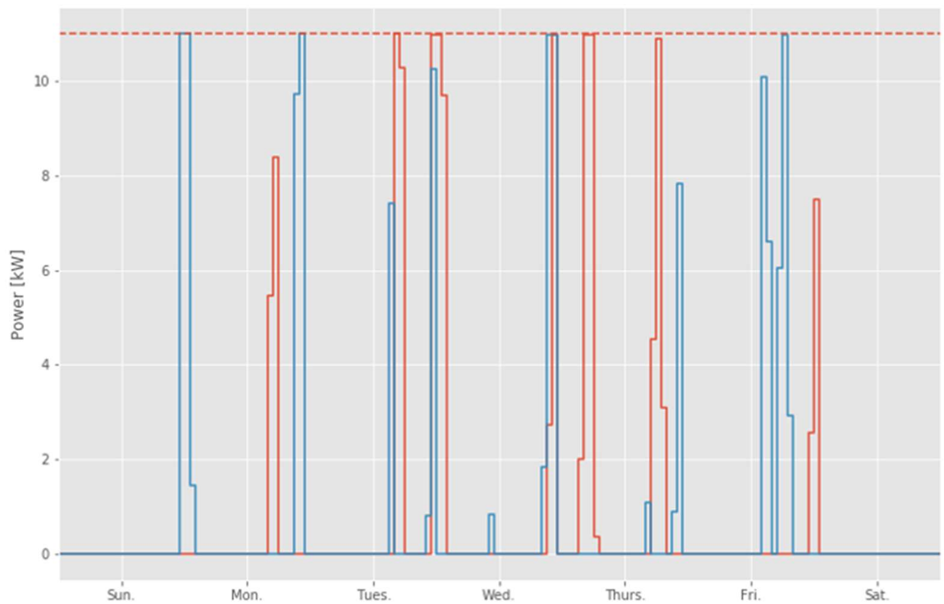

Figure 42: Electrical power demand at two 11 kW charging stations from two electric vehicles based on Giacomo Pareschi's mobility demand model.

To allow for the abovementioned impact analysis of e-mobility on the energy hub two things need to be clarified: 1) How much electricity does each electric vehicle demand for its operation? 2) When are the electric vehicles not operated, but available for recharging at the energy hub? To answer this, an energy demand and vehicle availability model was developed by Giacomo Pareschi (LAV Zurich) during his research in the *Electricity-based mobility* (EBM) project funded by *Competence Center Energy and Mobility* (CCEM). His work is based on the *Mobility and Transport Microcensus* (MTMC) and offers a minute-resolved representation of the availability of the vehicles and their daily energy demand. Giacomo Pareschi provided his model outputs in adjusted form for the purpose of the analysis. Figure 42 shows the derived electrical power demand of two electric vehicles at two 11 kW charging station for a week under the assumed uncontrolled (*plug&charge*) charging scheme. Note that smart charging is not available in this case study.

The cumulative electricity demand profile from the nine electric vehicles of the building under study is depicted in Figure 43 for every Tuesday of a year. One can clearly see a high number of high load hours in the evenings around 6pm, where there is little load occurring in the night / early morning hours (3am-6am). This is because people tend to come home and potentially charge their vehicles either at noon or in the evening. In an uncontrolled charging scheme, the batteries of the vehicles are then charged at the rated capacity of the charging station (here 11 kW are assumed) until they are fully charged. Since the charging under typical circumstances only takes some hours, there are only few morning hours in which the charging is still happening.

This concludes the section on mobility demand modelling for this case study. Therefore, the demand side characteristics are defined and the supply side optimization of the energy hub can be performed.

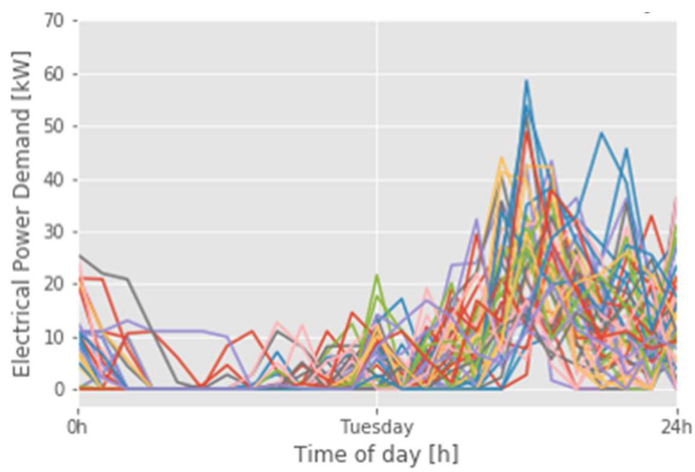

Figure 43: Cumulative electricity load profile for every Tuesday of a year from nine electric vehicles in the building under investigation.

10.1.3 Effects on Asset Sizing

As stated before, we want to investigate the impact of e-mobility and the effect of CHP system availability on the system. The first indicator that enables an impact analysis is the impact on the optimal sizing of the assets.

Figure 44 gives an overview of the results of the optimally installed asset sizes in terms of their input power when optimizing purely for cost reduction. Some general insights hold for all cases:

- The cost optimal stationary battery size (BAT) is 0 kWh in all cases.
- The optimization was set up to only include one of the heat pumps, i.e. either ASHP or GSHP can be selected. The ASHP does not get installed, but rather the GSHP.
- All other technologies, if available, get installed in a cost-minimal scenario. This results in a wide pallet of technologies to deliver the demanded energy.

Comparing the red (no CHP) and blue (CHP) bars (no e-Mobility), it becomes clear that:

- The CHP is part of the cost-minimal solution if available.
- Other heat supplying converter technologies (GB, ORH, GHSP) either keep their optimally installed size (ORH) or reduce their optimal power rating (GB, GSHP). This suggest that the newly installed CHP takes over some of the heat supply in the system as it become available.
- Other electricity supplying technologies (eGrid, PV) are reduced in their optimally installed capacity. That implies that the CHP also takes over some electricity generation functionality and is in line with the point made above.

- Especially the change in optimal installed capacities of the gas boiler (GB), the electrical grid (eGrid) and the photovoltaics system (PV) are quite large with a decrease of roughly 30%, 50% and 50% respectively with the advent of the CHP system.

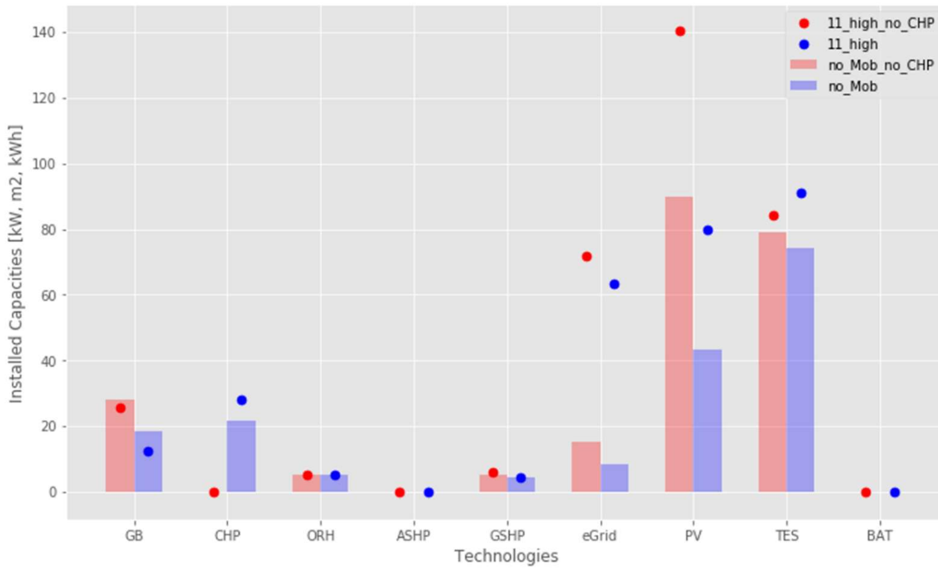

Figure 44: Result of the cost-optimal optimization of the energy hub: optimally installed energy asset sizes for the four cases of full (dots) / no (bars) e-mobility and no (red) / one (blue) CHP system available. (units: GB, CHP, ORH, ASHP, GSHP, eGrid in kW of input power, PV in m^2 and TES, BAT in kWh of storage volume)

When comparing the red bars (no CHP and no e-Mobility) and the red dots (no CHP, but strong e-Mobility) one can:

- Only see a small impact on the thermal asset installation sizes.
- See large impact on the optimally installed capacity of the electrical grid connection and the PV system. Namely, a roughly four times increase in eGrid connection capacity and 60% increase PV installation size when EVs are present.

For the comparison between the case of strong e-Mobility (dots) without a (red) and with a (blue) CHP being available certain aspects become evident:

- The optimal CHP size is also larger than zero. It is even increased compared to the no e-mobility case.
- As before, the other assets that supply thermal energy demand are thus reduced in size or stay on a similar level. Especially the gas boiler decreases in capacity.
- As for the electricity supplying assets, the installation of a CHP system leads to a reduction in installed capacity of the electrical grid connection, but mainly a reduction of PV installation size (roughly 50% decrease).

10.1.4 Effects on Energy Flow

In the next section the annual energy flow outputs of the assets are compared instead of the installed capacities. This gives insight into the operational mode of the assets.

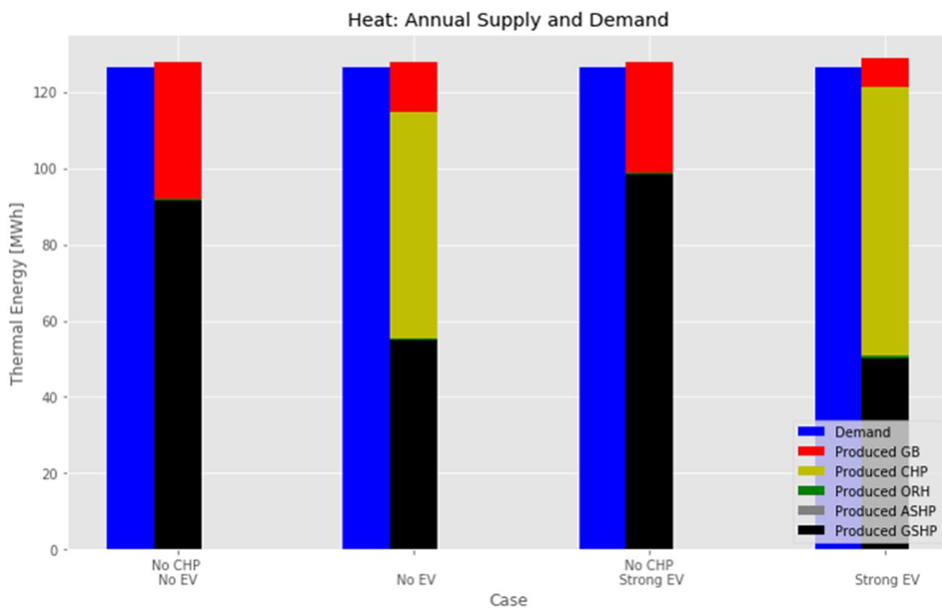

Figure 45: Annual sum of thermal demand and supply energy flows.

Figure 45 depicts the annual sum of thermal supply and demand energy flows by converter type for the four investigated cases. The thermal energy demand (blue) is the same for all cases, the thermal energy provision is however affected by the cost-minimal choice of installed capacities. In the reference case (no CHP, no e-Mobility), shown in the leftmost column, the majority of the heat is supplied by the ground-source heat pump. The remainder is almost exclusively supplied by the gas boiler. A very small fraction (barely visible) is provided by means of the electric resistance heater, which acts as an inexpensive auxiliary peaker.

In the second case a CHP system is available and is installed for a cost-minimal system. It reduces the heat provision of both the gas boiler and the heat pump and delivers roughly half the thermal energy supply to the building.

Jumping from case one (no CHP and no e-Mobility) to case three (no CHP, but strong e-Mobility), the heat provision shares are just slightly influenced towards more supply from the heat pumps and less supply from the gas boiler. This is probably cause by the larger installation of PVs, so that more excess electricity is available for thermal generation in non-charge hours.

When comparing the second (CHP, but no e-Mobility) to the fourth case (CHP and strong e-Mobility) a small increase in heat provision from the CHP can be seen in case of strong e-Mobility.

The annual electrical energy provision in Figure 46 shows more radical changes over the four cases. Between the left two cases without e-Mobility and the right two cases with e-Mobility one can see the

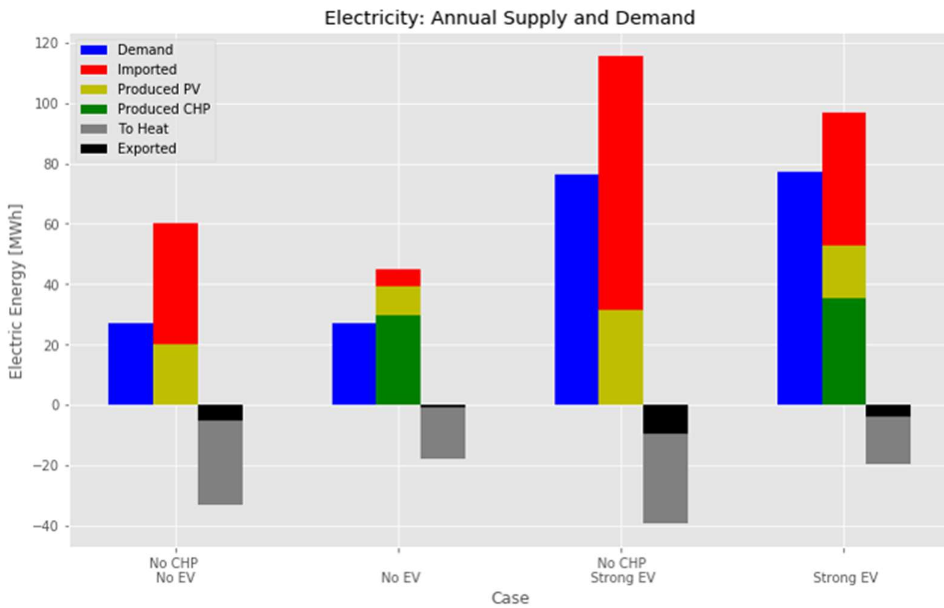

Figure 46: Annual sum of electrical demand and supply energy flows.

large increase in demand for electrical energy (blue columns). In all cases the electrical energy provision exceeds the nominal electricity demand quite substantially, since a rather large fraction of the imported or produced electricity is subsequently used to supply thermal energy to the building (gray, negative columns) e.g. via a heat pump. If a CHP system is available, it takes over a large proportion of the electrical energy provision in the energy hub. This effect is stronger in the no e-Mobility case. Electricity generation is also a part of the cost-minimal solutions in all cases. However, if a CHP system is available and consequently installed, the PV loses importance. That is the CHP replaces the PV system as a means of inexpensive electricity generation to some extent. In case there is no CHP available electricity from the grid plays a major role to supply the electricity demand. The introduction of e-Mobility increases this effect. The inclusion of a CHP system can reduce the dependency of the energy hub on the electrical grid quite a bit.

10.1.5 Conclusions for Future Work

Since the emission levels were ignored at this point of the investigations, which may lead to unintended designs and operational strategies, the emission performance was later included as an objective into the optimization tool. Further, the analysis of the situation in a single building, can be studied exemplary to understand the dependencies in the system and provide an entry to conduct plausibility checks on the model. It can however not tell the complete picture. Therefore, the analysis was later (in the project) expanded to include more and more varied buildings as well as sensitivity studies on uncertain parameters.

10.2 Optimal Asset Sizing Impact Study on Multiple, Random Buildings

In the previous section the impact of CHP availability and of e-Mobility were assessed in an energy hub of a single randomly selected multi-family building. In this section the results are tested in a broader manner on a set of 19 buildings to evaluate the impact of changing parameters, such as building size/shape, occupancy, and specific energy demand.

10.2.1 Energy Demand Modelling

Analogously to before, the energy demand of the newly selected buildings must be modelled in an hourly resolution. Therefore, a set of buildings needed to be defined. This was done by randomly selecting a

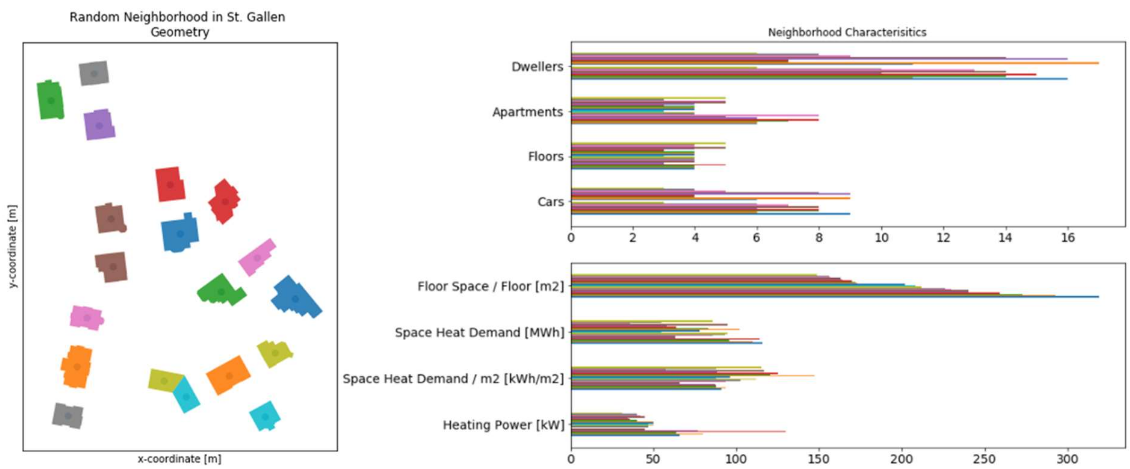

Figure 47: Overview of the buildings and their specifications of a randomly selected neighborhood in St. Gallen

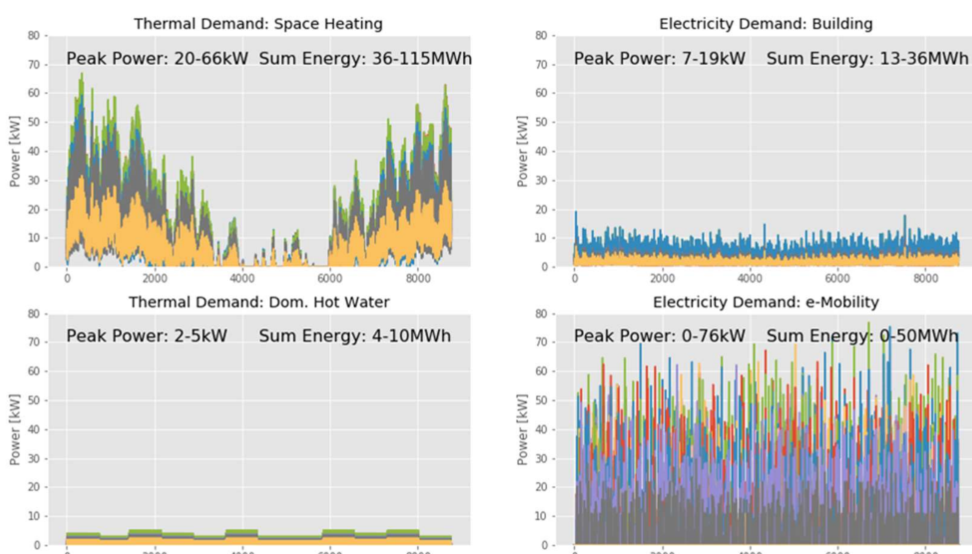

Figure 48: Energy demand profiles from the 19 randomly selected buildings and their respective e-Mobility in St. Gallen over the course of one year (8760 hours).

neighborhood from a building dataset provided by the City of St. Gallen's utility[7]. Figure 47 gives an impression of the range of building and mobility variation drawn.

The same demand side modelling approach as in the previous section was followed to obtain the demand side load profiles for all buildings. The load profiles of the buildings can be seen in Figure 48.

To get a better understanding of the magnitudes of energy demands, the annual sum of energy demands of the above-described profiles in given in Figure 49. Clearly the largest variation occurs in the heating

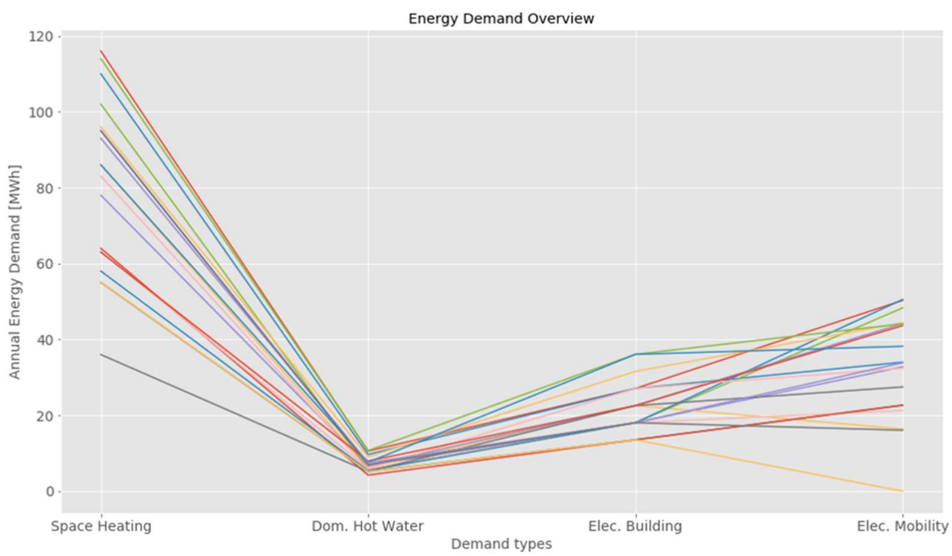

Figure 49: Annual summation of the residential energy demand profiles per demand category for the case of strong e-Mobility. One lone represents one building.

demand segment. Low variation is modelled in the domestic hot water segment and intermediate variation of annual demand is assumed for the electrical stationary energy demand. The electricity demand for e-Mobility is shown for the strong e-Mobility case. For the case of no e-Mobility this collapses to zero for all buildings as the vehicles in those cases operate on gasoline.

10.2.2 Optimal Asset Sizing

To assess the impact of varying energy demands on the optimally installed asset sizes for the four cases, ranging from no CHP + no e-Mobility to CHP + strong e-mobility, the cost-minimizing optimization was repeated for all 19 buildings and the optimally installed asset sizes reported in the known way. Figure 50 shows the results of those simulations. One line represents the installed asset combination of one building. Additionally, a box plot is overlaid to point out the variability of the selected asset sizing. One can clearly see that some technologies are rather confined (ORH, GSHP), whereas other technologies show a large variability in their optimal design capacity (GB, PV, TES). Further, two technologies never get installed in a cost-minimal system: ASHP and BAT.

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[7] Harry Künzle and team from Stadtwerke St. Gallen (https://www.sgsw.ch/)

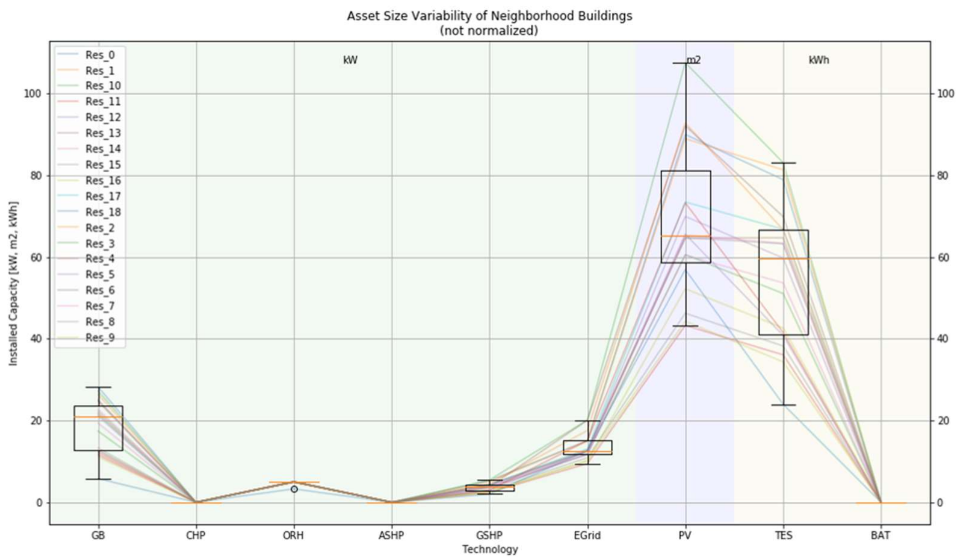

Figure 50: Non-normalized cost-minimally installed assets for the reference case of no e-Mobility and no CHP.

If one now normalizes the installed asset size by the yearly total energy demand, which is comprised by electrical and thermal energy demand, the intra-technology variability gets reduced. The result from the normalization can be seen in Figure 51. This could be potentially used to define rule-of thumb

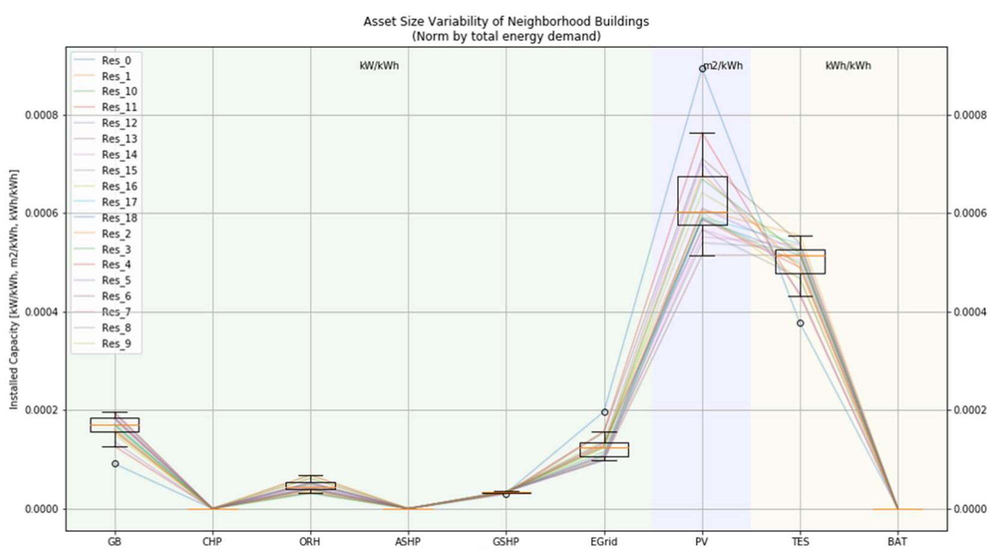

Figure 51: Normalized cost-minimally installed asset for the reference case of no e-Mobility and no CHP.

design rules or to initialize / warm-start the optimization problem with realistic values to reduce computational times. In the interest of brevity not shown in this report, the results from normalization improve when normalizing thermal assets by the annual thermal demand and the electrical assets by the annual electricity demand.

Comparing the investigated cases, we see the same overall trends as in the analysis for the single multi-family building in the Section 10.1 of the report: 1. For all buildings investigated a CHP system gets selected as a part of the cost-minimal solution, if it is available (cf. Figure 52 and Figure 53). This mainly reduces the optimally installed gas boiler, PV, and e-Grid connection size cf. Figure 50.

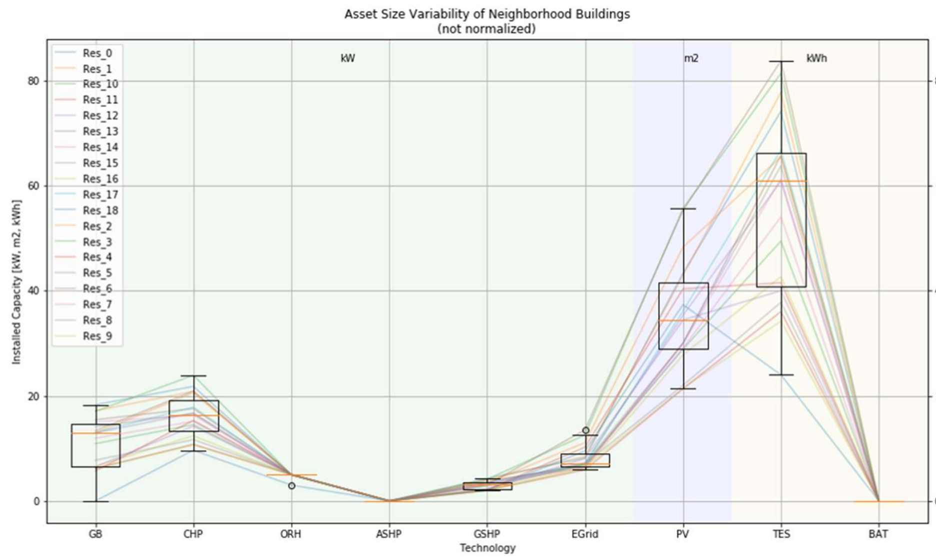

Figure 52: Cost-minimally installed assets for the case of no e-Mobility, but CHP availability.

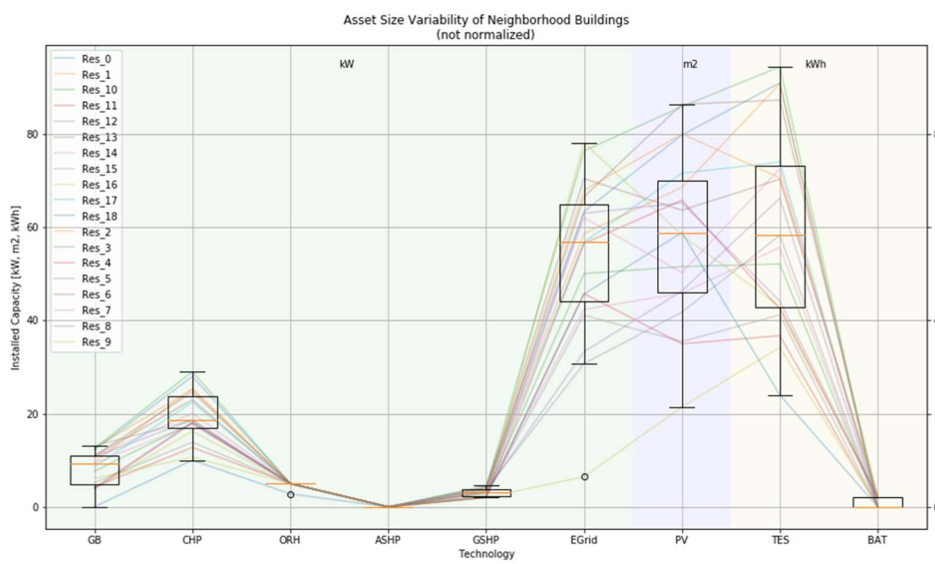

Figure 53: Cost-minimally installed assets for the case of e-Mobility and CHP availability.

Adding our (rather strong) 100% vehicle electrification scenario to the analysis leads to the optimal asset sizing depicted in Figure 53. Also, here the same trends as before hold. E-Mobility increases the optimally installed CHP capacity a bit. Therefore, GB installed capacity reduces a bit. Mainly however, the large increase in electricity demand leads to an increase in PV and especially e-Grid connection size. Further, the variance of the optimally installed capacity, both for PV and e-Grid connections, increases quite a bit in case of e-Mobility.

This analysis suggests several things:

1. The overall trends and explanations found in the single multi-family building analysis were found to hold for the wider test on 19 randomly selected buildings.
2. Ignoring cost for increasing levels of complexity by increasing the number of assets installed at an energy hub, the cost-minimal solution is a solution that includes many energy assets.
3. CHP plants offer an inexpensive way to supply energy to a building and its mobility, since they are installed whenever they are available in the cost-minimal solution.
4. CHP systems replace gas boilers and PV systems in cost-minimizing energy hubs.
5. Technology availability can play a rather large role when sizing assets optimally. Especially when little alternatives to supply a certain energy stream are available, flexibility is restricted.
6. Optimal technology sizing trends for a given set of technologies seem to be rather robust when normalized against their respective energy demand. This is less true for e-Mobility. A more detailed analysis would however be necessary to confirm this.
7. Strong e-Mobility cause especially the optimally installed PV and eGrid connection to increase, with the grid connection being impacted the most. The available eGrid connection power was hence noted as an important quantity to keep in mind for future investigations.

Next to the identification of the importance of the grid-connection in the energy hub, the large effect on the optimally chosen PV size was unexpected. This led to a further investigation of the utilization of the available PV space, which results can be seen in Figure 54.

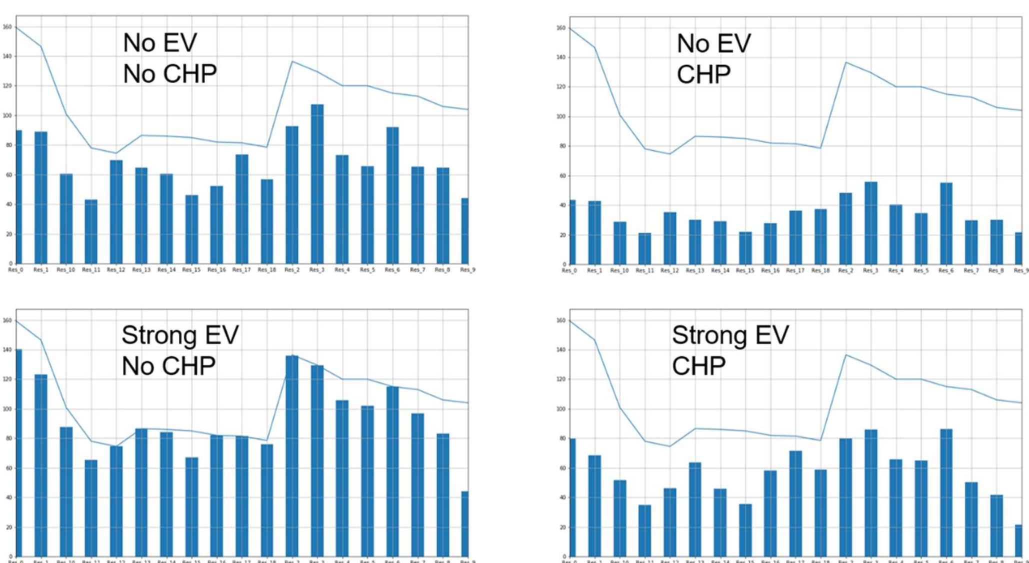

Figure 54: PV utilization in the four cases for all 19 buildings. Optimally installed PV size is indicated by a columns per building. The maximally available PV size for that building is given by the thin blue line.

The four investigated cases show varying degrees of maximal PV size utilization. The case in which the PV installation size is the least critical, i.e. the furthest from the maximum for the buildings, is the case of no EV but a CHP system available. Since the CHP reduces the amount of optimally installed PV and no e-mobility causes no additional electrical demand, this is quite logical. On the other side of the spectrum, the case without a CHP but large e-Mobility demand shows the largest PV installation rates. In many cases the available PV area is fully utilized. The other two cases show intermediate levels of PV area utilization. The availability of a CHP roughly compensates the need for additional PV installation in case of e-Mobility.

10.2.3 Intermediate Conclusions

This segment studied the influence of CHP availability and the proliferation of EVs for a set of varied buildings located in a neighbourhood. The results show that there is a large variability on the building energy demands, especially regarding the thermal and e-mobility demand. These variations in the energy demand causes variations in the optimally selected energy supply technologies. Variations in the optimal size of PV, TES and eGrid connections are the largest. Nevertheless, general trends of the amount, type, and approximate optimal size hold across a range of building sizes. As in these simulations the electrical grid connection is a decisional variable of the optimization problem, i.e. an easily adaptable component, which is inherently an inexpensive asset offering peaking capability, it is identified as an attractive component to upgrade when strong e-mobility scenarios are present. For later simulations in the project this quantity was restricted to only assume normed values based on the building sizes or cut-off the connection to the electrical grid.

10.3 District / Neighborhood Analysis

To advance the project towards larger scales, in accordance with the project proposal, we switched the focus from single buildings to a multi-building analysis. From an energy asset installation point of view the buildings that share a common source of energy of energy provision can be thought of as a neighbourhood or district. Three types of small-scale neighbourhoods can be distinguished: They can either be a neighbourhood that forms an electricity sharing community (Zusammenschluss für Eigenverbrauch, ZEV) in order to act as a single entity towards the electric utility and manage their on-site electricity production and consumption autonomously. A ZEV promises higher PV-self-consumption rates, thus a reduced dependency on the utility and lower overall cost. Another form of energy sharing on a small-scale level is the sharing of heating infrastructure. Here typically the heating system is installed in one of the community's buildings, produces heat locally and distributes the heat to adjacent buildings via a thermal energy grid. The third energy sharing community in our view would be a vehicle/mobility sharing community. In our analysis we however focus on the first two sharing concepts and assume that thermal energy sharing communities would also form electricity sharing communities.

10.3.1 Building Selection

The majority of buildings in St. Gallen are individual heating points, i.e. they supply themselves with the heat that they generate on-site (82% of all single-family buildings, slightly lower for multi-family buildings). A by far smaller portion is heated by a central heating power plant via a district heating grid (17% of all single-family buildings, slightly higher for multi-family buildings). The third class of buildings, with very low proportion of all St. Gallen buildings (1% of all single-family buildings, slightly higher for multi-family buildings), are local thermal energy communities that possess the infrastructure to heat themselves by a shared distributed energy asset. The building of this third type were identified and extracted from the overall building dataset.

A second set of filters to reduce the number of buildings in question was applied. Since energy efficiency is typically a larger problem in older buildings, energy communities with an average year of construction of 2000 and younger were excluded from the analysis. Further, to keep the techno-economic assumptions in a suitable region, energy communities of more than 50 MWh electricity demand per year and gas demand of more than 500 MWh per year were excluded. Lastly, only energy communities that already have access to a gas grid were included.

Applying this two-step filtering procedure 17 single-family buildings (out of 3212 in St. Gallen) and 15 multi-family buildings (out of 4984 in St. Gallen) that are connected in a total of 9 energy communities were obtained. These buildings in their respective energy sharing communities were then assess as individual energy hubs demanding the sum of energy demand profiles within the community.

10.3.2 Mobility Demand Generation

As before, it is crucial to model not only the stationary energy demand of the energy hubs but also the mobility demand. Following a similar approach to the mobility demand modelling by Dr. Giacomo Pareschi described above, the 2015 *MTMC* was used to build a household size specific mobility demand patterns for the subsequent analysis. This work was done as a master thesis project by Anina Döbeli (Döbeli, 2019) and used a total of five interlinked machine learning models to understand and model the mobility demand behaviour of households and individuals as a function of classical determinates like age, gender, marital status, household size. Starting from the *MTMC* she derived the number of vehicles and driving licenses held by the Swiss population. Based on this knowledge she then estimated the daily trip distance, trip duration and departure time, which serve as the mobility demand and charging availability model in subsequent sections.

Figure 56 illustrates the variability and average values of identified driving distance over all drivers and subsets of drivers, from which household size specific mobility demand patterns for an annual mobility

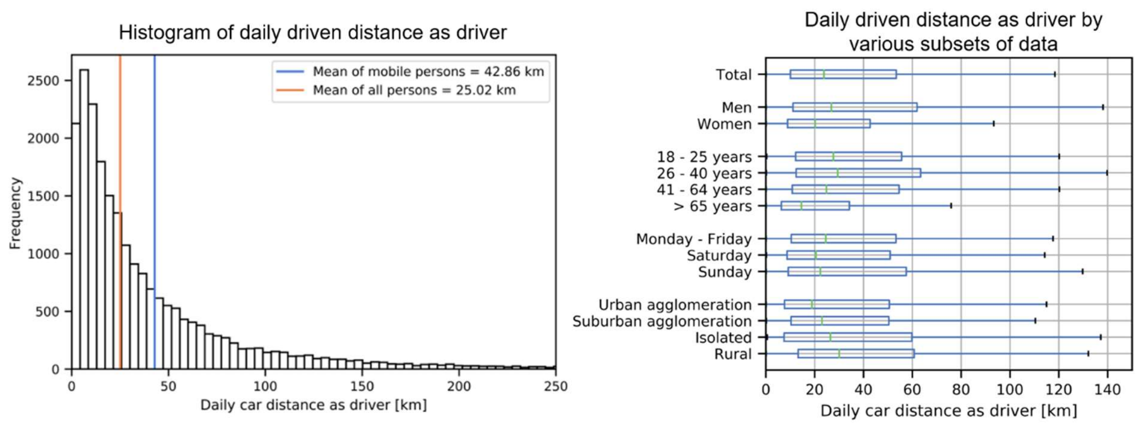

Figure 56: (Left) Histogram of modelled daily driven distance as a driver of a vehicle in Switzerland. (Right) Modelled daily driver distance as a function of dataset features.

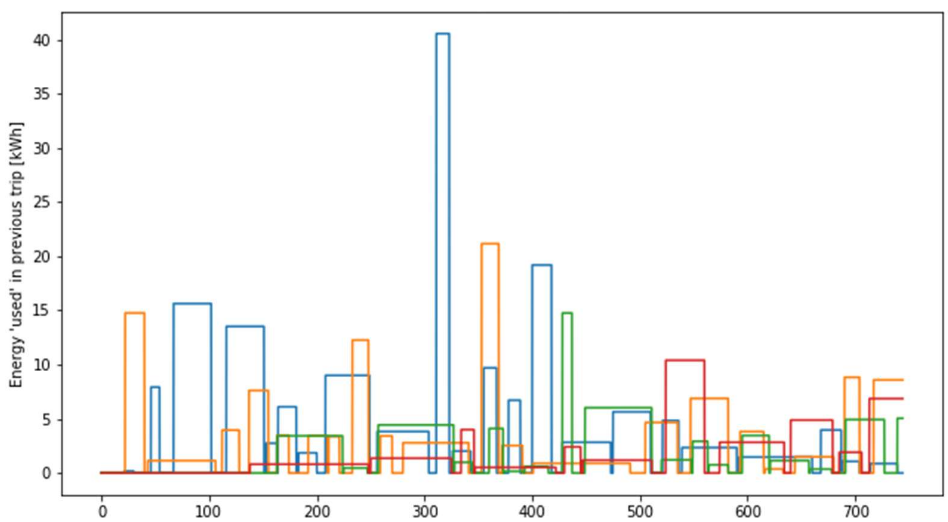

Figure 55: Charging availability windows (non-zero time periods) and associated energy demand (y-axis) from previous trip (zero value time periods).

were derived. The resulting charging availability windows and associated energy demands can be seen in Figure 55, where every coloured line represents the charging availability time window and the associated energy demand of a single car. During times of energy demand, the vehicle would like to charge the indicated amount of energy to return to its battery's previous state-of-charge (SOC). During times in which the charging energy demand is indicated as zero, the vehicles are not available for charging, because they are currently not at home. So, high columns indicate a high energy demand from the vehicle's previous trip. Wide columns indicate long windows of charging availability for the car's battery to recharge.

10.3.3 Charging Technology Assumption

After modelling the mobility demand and charging availability, it is important to also define a charging strategy, since the charging strategy will impact when and how quickly an EV's partially depleted battery will be recharged. This has implications when the on-site electricity generation assets are operated or when electricity is drawn from the electricity grid.

One can distinguish two types of charging strategies, which offer different levels of sophistication:

- Uncontrolled charging (also known as "plug & charge")
- Controlled charging (from simple smoothing to e.g. cost- or emission-aware "smart charging")

Under uncontrolled charging the charging process of the vehicle typically begins as soon as the vehicle is connected to the charging station and at the maximum permissible charging rate. This charging is the least sophisticated but charges the vehicle as quickly as possible. Controlled charging on the contrary

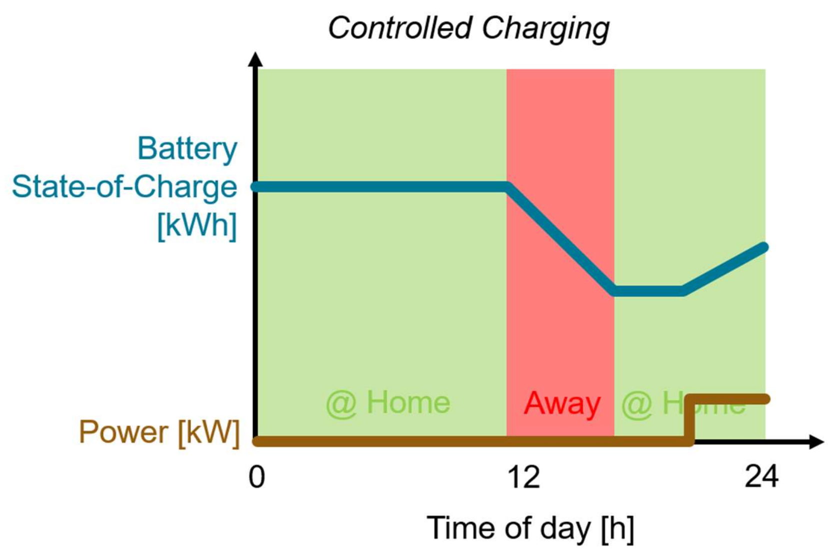

Figure 57: Controlled EV charging scheme that delays the start of charging from the time of arrival at home until after the electricity price drops to the lower tariff at night.

can delay the charging process or reduce the rate of charging in case the charging process does not need to be finished as quickly as possible. In a simple version the start of the charging process could for example be delayed until low-tariff electricity is available at night. More sophisticatedly, the charging could also be postponed to occur during hours of sunshine in case a PV system is installed on-site to maximize the utilization of solar energy. These rather sophisticated charging strategies are often summarized under the term "Smart Charging" and need foresight to work. An example of a delayed charging schedule is shown in Figure 57.

For the remainder of this section, smart charging that either minimizes overall system cost or overall CO_2 emissions or a mix thereof will be used. Figure 57 illustrates the delayed begin of the charging process in a cost-minimizing optimization scheme until the low tariff electricity is available in the evening. The charging rate per charging station is assumed to be 11 kW for all subsequent results.

10.3.4 Supply Technologies and Assumptions

Besides the demand side, also the supply side needs to be modelled for the optimization process. The energy hub from Figure 7 is used as a basis, however the following alterations are made:

- The simple electric heater (ORH) was omitted as a converter technology from the analysis.
- The buildings' connections to the electrical grid were fixed to typical values as a function of the number of dwellings in the energy hub instead of having them as optimization variables in accordance with the method in the main section of the report. That is, there is now a fixed, non-optimizable limit on the maximum import and export capacity of the electrical grid, dictated by the typical cable/fuse installation at the main connection point of the energy hub.
- Smart charging stations are included instead of uncontrolled *plug&charge* charging stations.

10.3.5 Investigative Spread of the Energy Hub Analysis

With this set of demand profiles and supply converter technologies the following set of analyses was run for nine energy hubs containing two building types (single- and multi-family buildings), three mobility scenarios with five randomized mobility demand profiles each and seven available technology combinations. This results in 135 (9*3*5) runs per technology combination. Each described optimization problem consists out of another eight sub-optimization runs that scan the solution space from cost-minimal to CO_2-minimal solutions.

10.3.6 Optimization Result Status

These optimization runs can, in a first step, be analysed with respect to the overall outcome of the optimization. We distinguished three cases; 1. An optimal solution was found, 2. A suboptimal solution was found 3. The solver did not find a feasible solution. Figure 58 shows the optimization outcome as a

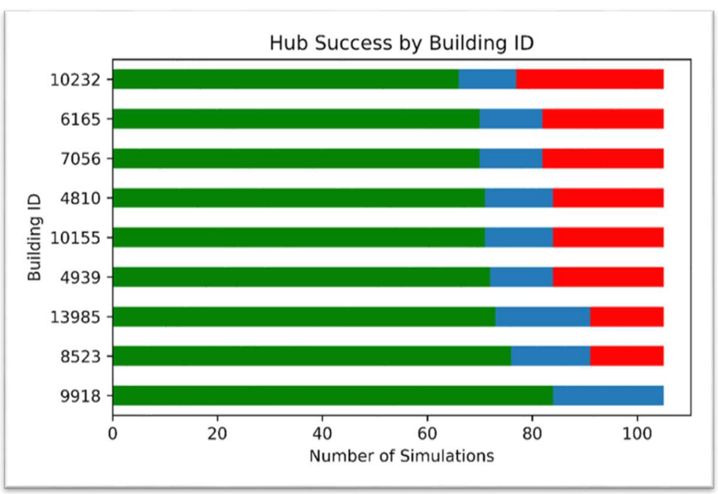

Figure 58: Optimization outcome as a function of the energy hub (Green=optimal, blue=suboptimal, red=infeasible)

function of the building ID of the energy-supplying building in the nine investigated community energy hubs. Almost all energy hubs (except for the last) exhibit infeasible solutions. However, the rate of failure is not constant over the remaining energy hubs but varies. This hints at an infeasibility of the problem due to too restricting constraints. Further, all energy hubs exhibit suboptimal solutions. This means that the problem is feasible, but the found solution at the end of the predefined solver time limit was non-optimal. More computational power or a longer time limit might transform suboptimal solutions into optimal ones. Note that all simulations were performed on the EULER Cluster[8], where not necessarily the same hardware is allocated to each simulation run. Also note that the maximum solver time was set to 20 minutes for each optimization sub-problem, so that a maximum of 160 minutes was available for the problem to solve in the worst-case scenario.

Looking at Figure 59 one can see the influence of the mobility setting on the solution outcome of the optimizations. The label on the y-axis represents the mobility setting of the respective simulation run, where the first number stands for the number of electric vehicles in the scenario and the latter number

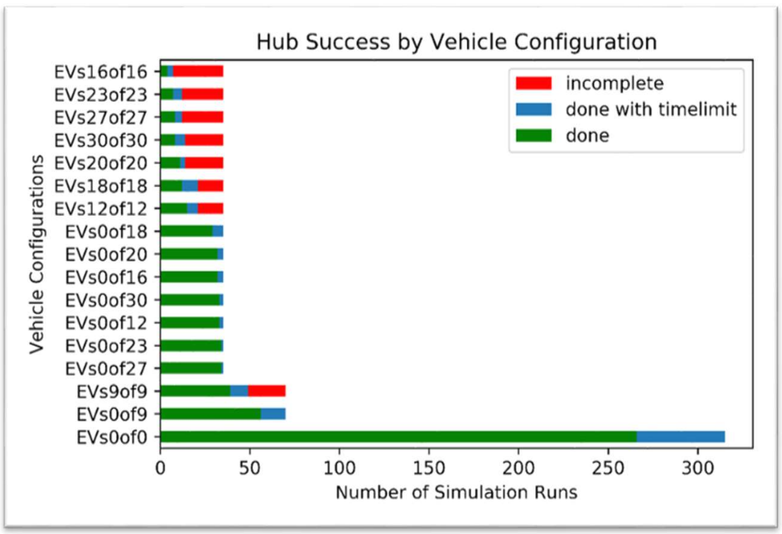

Figure 59: Optimization outcome as a function of the mobility setting (Green=optimal, blue=suboptimal, red=infeasible; EVs0of9 = zero of 9 vehicles were EVs)

stands for the total amount of vehicles in the scenario. The infeasible solutions exclusively come from the cases in which e-mobility is present. The e-mobility demand therefore seems to produce situations in which the energy hub cannot supply the necessary energy to the vehicles for them to fulfil their mobility pattern. This could stem from the fixed battery sizes of the vehicles which were set at their minimum capacity to fulfil the longest trip on a full charge + 10 kWh of buffer. If a vehicle's mobility demand pattern comprises two relatively long trips shortly after one another, then the available charging window in between is not enough to recharge the battery sufficiently for the next trip. Another, yet less likely, explanation is that the maximum power generation plus the maximum import capacity are not sufficient to cope with the simultaneous demand of many vehicles. Since the CHP and the stationary battery however offer large reserves to supply power on demand, yet neither large batteries nor large CHPs are installed, the initial explanation seems more adequate.

[8] Visit https://ethz.ch/services/en/it-services/catalogue/server-cluster/hpc.html for more information.

To further assess this, the impact that technology availability has on the feasibility and optimality of the simulation runs can be plotted in a similar way as a function of technology portfolios that where available (see Figure 60). The labels indicate the technology packages at disposal: Technologies separated by underscores are individually selectable. If multiple technologies are not separated by underscores, then only one of those technologies is selectable for the system configuration. Interestingly, the number of infeasible solutions does not depend on the technologies that where available. The simpler technology solutions tend to provide more optimal solutions within the solver time limit. Runs including heat pumps

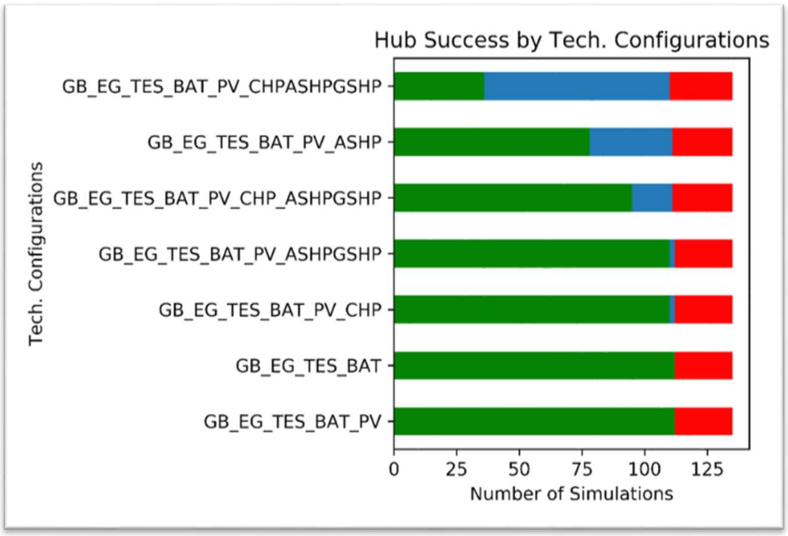

Figure 60: Optimization outcome as a function of technology availability (Green=optimal, blue=suboptimal, red=infeasible)

or technology packages from which only one technology can be chosen quite often return with suboptimal solutions.

These results give a good indication why the simulations come back either suboptimal or infeasible. A more detailed analysis could support this further.

We can learn that the increase of technological complexity in the simulation leads to more problems with respect to solving the optimization problems. In retrospect, we believe that an increase of the computational time limit set to reduce the overall computational time would alleviate many if not all cases of suboptimality. However, a trade-off between the desired optimality, the computational requirements and the overall justifiable parameter variations must be found.

10.3.7 Key Performance Indicators and the Solution Space at the Example of a Single Energy Hub

In this next section the outcome of the simulations will be discusses at the example of one energy hub, but the other simulations resulted in similar solutions. The exemplary energy hub houses 12 people and in our scenario of 100% motorization and vehicle electrification also 12 electric vehicles which drive roughly 7000 $km/year$ each.

Clearly, the reference case in which no mobility is considered (black) in Figure 61 emits the lowest amount of CO_2 emissions and has the lowest overall cost, since the energy demand of this hub is inherently smaller. When adding 12 ICEVs to the energy hub, not only the CO_2 emissions rise, but also then EAC. Compared to the previous two cases, the case of e-Mobility exhibits slightly higher cost but significantly lower CO_2 emissions than the ICEV case. Its CO_2 emissions are almost as low as the case without mobility. Please note the following:

- The cases' squares indicate the cost minimal solution of the base technology case, which comprises a gas boiler (GB), a connection to the electrical grid (EG), a thermal energy storage (TES) and a battery (BAT) as available, but not necessarily installed technologies.
- Here, only operational CO_2 emissions are included, but embodied emissions of the EV batteries will also be discussed later in this section. (The main section of the report includes embodied emissions of all assets in all calculations)
- The equivalent annual cost are the total, 3% discounted cost over an investment period of 20 years broken-down into equivalent yearly cost.
- Stationary energy assets are assumed to have a lifetime of 20 years. PV and battery systems are exceptions with 30 and 10 years of lifetime respectively.
- Vehicles are assumed to have a lifetime of 15 years.
- At the end of the lifetime assets get replaced by the same components. If the lifetime exceeds the planning horizon, the linearly depreciating salvage value is accredited as a cash flow in the final year.

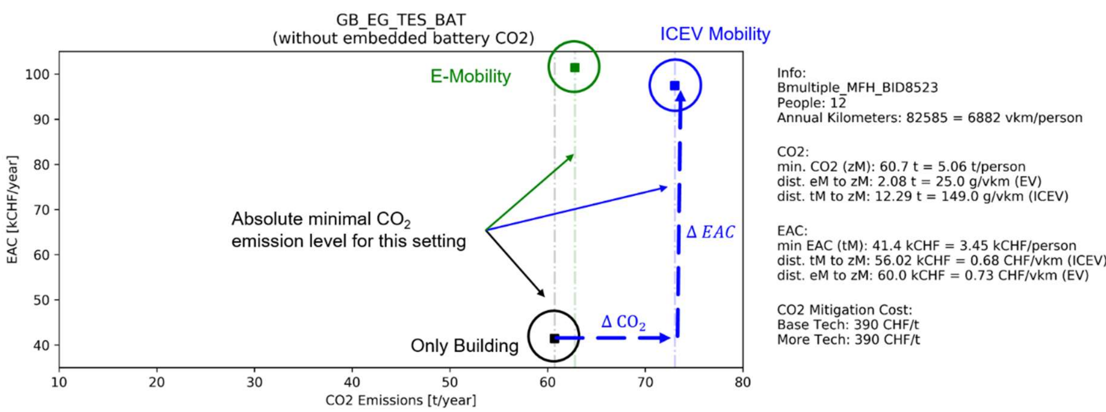

Figure 61: Key performance indicators (Equivalent Annual Cost and Annual CO2 emissions) of an exemplary energy hub of 12 residents for the base technology configuration and either zero cars (black), 12 ICEVs (blue) or 12 EVs (green)

- ICEVs are considered to have an investment cost of CHF 47'000, whereas BEVs with a battery of 60 kWh are estimated to cost CHF 10'000 more. However, the battery capacity in the simulation model is determined by the longest trip per year. This resembles the fact that short distance drivers will buy a vehicle with smaller battery capacity and long-distance drivers will buy vehicles with larger battery capacities. With changes in the battery capacity the overall cost of the EVs is adjusted accordingly at a rate of 166 CHF/kWh.
- The minimal CO_2 emission line is marked by the vertical dash-dotted lines. They result from the minimal CO_2 optimization and indicate the point where no more emission reduction can be done from a technological point of view, i.e. without other technologies, adjusted consumer behaviour, etc.

- On the right-hand side some key values and differences between the cases are visible. The abbreviations zM, tM and eM stand for zero Mobility, traditional Mobility (i.e. ICEVs) and e-Mobility (EVs).
- The marginal mitigation cost of switching from the traditional Mobility case to the e-Mobility case are rather high (390 $CHF/tCO2$) as compared to other CO_2 mitigation measures (also in other sectors).

In the next figure, Figure 62, the optimization results of the same energy hub with a slightly expanded technology set are shown: a photovoltaic system is now at disposal and allows for asset sizing variation and thus optimization for lowest cost and lowest CO_2 emissions.

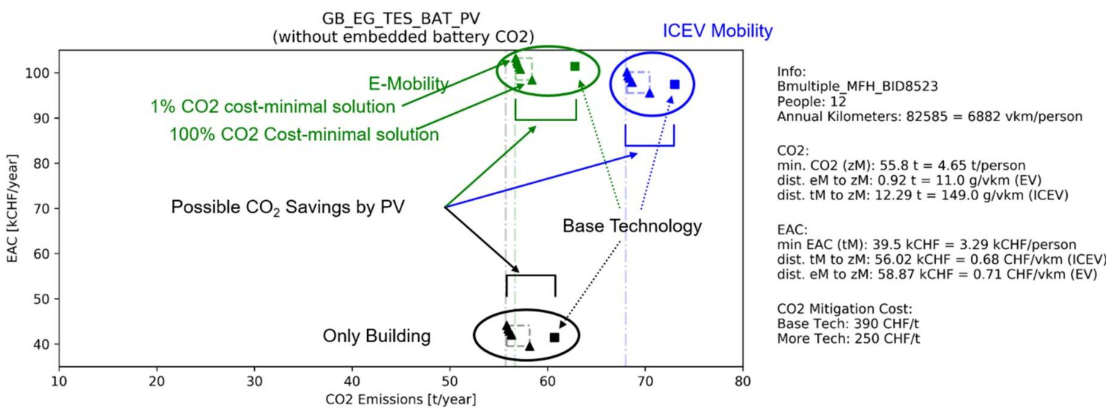

Figure 62: Key Performance Indicators for energy hub with additional PV system available.

For the purpose of a reference the cost-minimal *Base Technology* solution for all three mobility cases is still indicated in the figure as a square marker. The energy hub solution's key performance indicators where a PV system was part of the available technology set are indicated by upwards facing triangle markers. Per mobility case eight results with increasingly stringent CO_2 constraints were computed. Therefore, eight upwards facing triangle markers are visible per mobility case. The triangle furthest down on the y-axis represents the minimal cost solution, whereas the triangle the furthest to the left, represents the CO_2 minimal solution that is accepted as the solution within 1% of the absolute minimal CO_2 line. To visually guide the reader these eight CO_2 constraint simulations per mobility case been placed inside a dashed box. The wider the dashed box, the larger is the CO_2 reduction potential from the least-cost to the least CO_2 emission case. The taller the box the larger is the absolute increase in total annual cost for that CO_2 reduction. Some interesting things are noticeable:

- The overall position of the solution results for the three mobility cases does not change substantially due to the availability of the PV system.
- However, the minimal cost achievable with the PV system lies below the minimal cost of the base case.
- Further, the minimal achievable CO_2 emissions are lower when a PV system is available.
- The overall reduction potential by means of a PV system is however limited. This is one the one hand due to the size constraint caused by the maximal roof area available, the limited production

window during the day and the year, and since the electricity demand makes up only a small fraction of the total CO_2 emissions.

- The CO_2 emission reduction potential (from the minimum-cost base case to the technology-rich minimum CO_2 emission level) is larger in case of e-Mobility as compared to the case without any mobility at all. This indicates that the overall systems profits from the availability of the vehicle s' batteries.

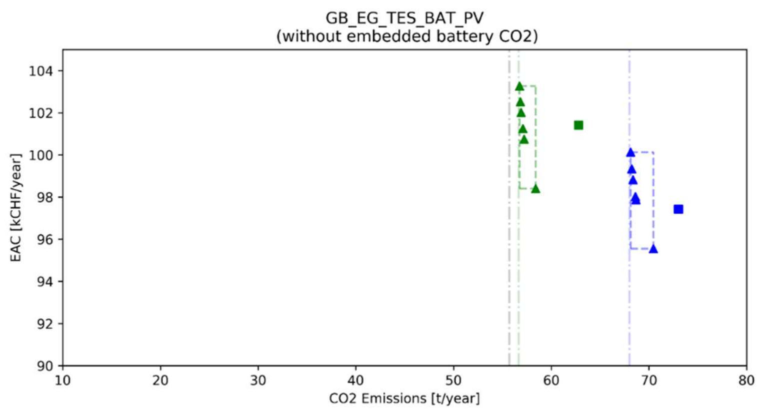

Figure 63: Key Performance Indicators of the Base Case + PV case

Taking a closer look at the same results of the previous analysis in Figure 63 one can notice that the CO_2 emission reduction from a PV system is rather expensive towards the vertical minimum CO_2 emission line. This is intuitive since the operational CO_2 emission reduction can only be achieved by installing a larger PV system that is bound to produce at times of sunshine and not necessarily when needed. The next step is then the rather expensive purchase of a battery system to minimize the on-site utilization rate of the PV produced energy.

In the next analysis a CHP system is introduced as another technology available to the optimization. Figure 64 shows the results of the analysis as compares to the base case and also the previous base technology + PV case. The black brackets show the size of the dashed box of the previous base

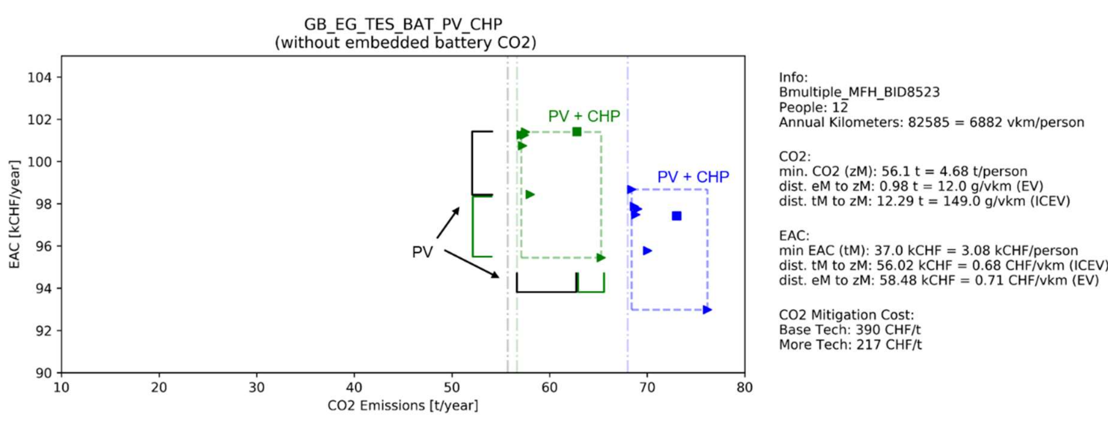

Figure 64: Key Performance Indicator Results from the Base Technology + PV + CHP system

technology + PV case. One can clearly see that the introduction of the additional CHP system expands the height and width of the dashed boxes. Therefore, the minimally achievable cost is lower in this new case, but the associated CO_2 emissions of the cost-minimal solution are higher than previously.

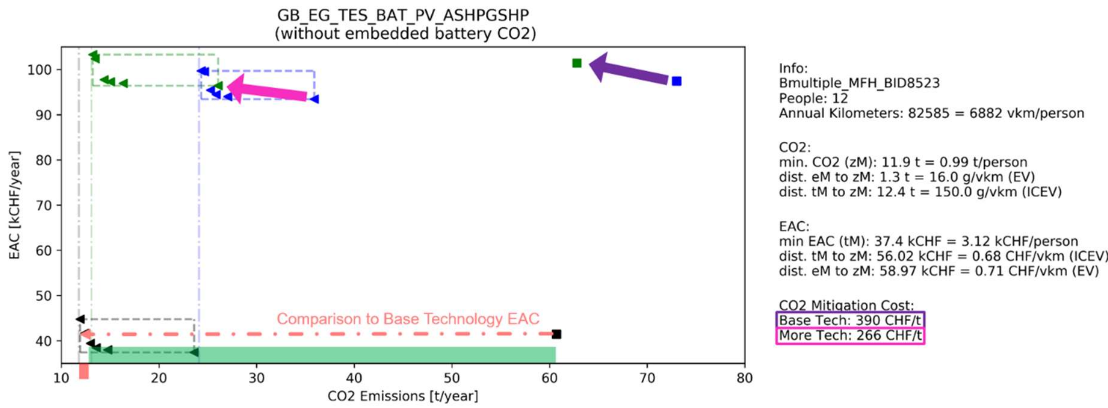

Figure 65: Key Performance Results of the base technology + PV + either ASHP or GSHP case

The last technology combination that is discussed in this way is the combination of the base technology set + PV + either an air-source or a ground-source heat pump (see Figure 65). Also, this case offers cost reductions as compared to the reference base with only basic technologies included. Further, even the cost-minimal solutions show large reductions in CO_2 emissions compared to the base case. When maximizing the CO_2 emission reduction yet another quite sizable emission reduction is possible at identical cost as the base case scenario. Only the last few percent of emission reduction cause the overall cost to surpass the level of the base case. Going from the cost-minimal solution with traditional mobility to the cost-minimal solution including e-Mobility, one needs to spend 266 $CHF/year$ and ton of CO_2 to reduce operational CO_2 emissions by another 10 $tons/year$.

Finally, the impact of the embedded CO_2 emissions from the EVs' battery systems was considered to indicatively illustrate their impact on the overall annual emissions. A CO_2 intensity for the batteries of 150 kg $_{CO2}$ / kWh was assumed. Embedded CO_2 emissions of other assets were omitted in this section of the report. Since these embedded CO_2 emissions only act as an offset to the findings rather than

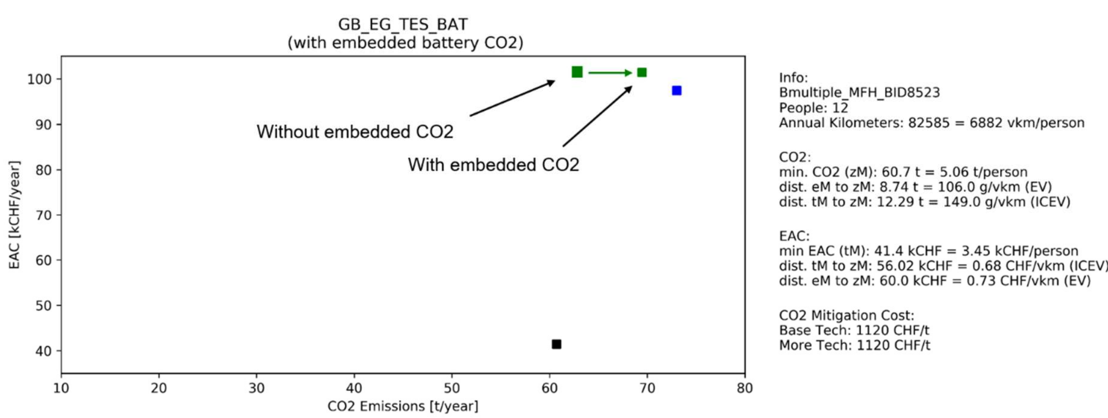

Figure 66: Effect of the additional, annually broken-down embedded CO_2 from the EVs' batteries

influence the optimization itself, the offset displayed in Figure 66 can be added to all scenarios which include e-Mobility in retrospect. This is the case as the vehicles' battery sizes are not optimization variables but pre-determined constants. The inclusion of additional CO_2 emissions from the vehicle batteries leads to an increase in CO_2 emissions and therefore CO_2 mitigation cost. In later optimizations in the project, the embodied emissions were added as fundamental and largely important emissions to the optimization tool. This is crucial for the interpretation of the results when comparing to cases of traditional/conventional mobility. Later optimizations also included the design of the EV batteries into the optimization problem. The embodied emissions of the battery, then influence the optimizations' objective function and must be taken into account a priori.

10.3.8 Effects on the energy flow from and to the electricity grid

In all assessed scenarios a connection to the electrical grid is available. This connection size is of predetermined size and varies with the number of apartments served by this connection. The utilization of the grid connection, however, is not predetermined but depends on the economic and ecologic relative attractiveness of using it to cover electricity demand compared to utilizing on-site energy assets for the same matter at any time of the simulation year. Two related factors which mainly impact the way the electrical grid is used are: 1. the technology availability for on-site generation and storage and 2. the ecological constraint set within the optimization problem.

Cost-minimal Analysis

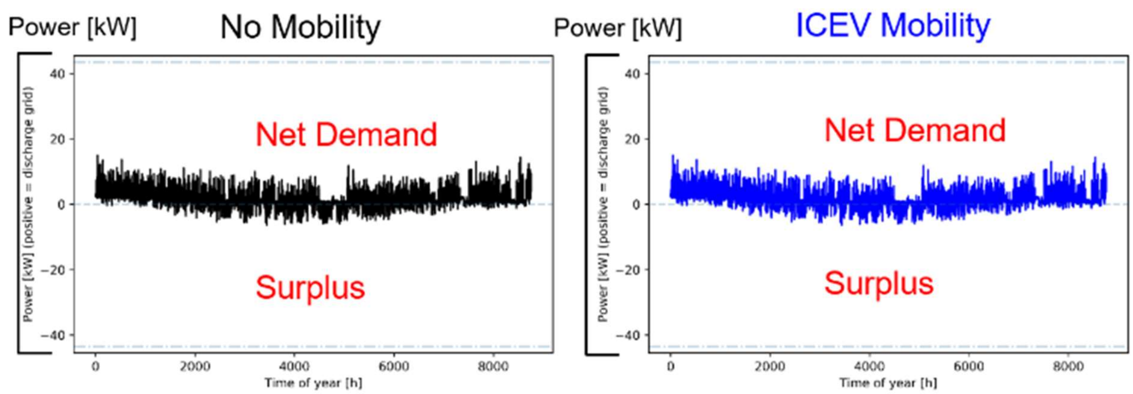

Figure 67: Import (Net Demand) and Export (Surplus) of electricity to and from the energy hub over one year. The left plot shows the situation for no mobility at the hub and the right plot shows the situation for the case of traditional mobility. In both cases cost-minimal base technology and PV systems are installed.

Figure 67 depicts the exchange of electricity with the electrical grid over the course of one year in a cost minimal configuration with base and PV technologies being available. During times of net demand, the energy hub imports electricity to supply its demand. During times of oversupply the energy hub exports electricity to the electrical grid. One can see that, as expected when including ICEV mobility, the grid exchange profiles look identical as the traditional, combustion-based mobility does not have an impact on the e-Grid exchange. Oversupply mainly occurs during summer when the output from the solar cells is larger. During winter the installed capacity of PV panels is not sufficient to allow for large export portions. Knowing from other analysis that not the maximum of PV panels are installed on the energy hub's roof(s) one can see the trade-off of installing a reasonable amount of PV to cover a large portion of the energy hubs electricity supply, while not excessively exporting during summer due to overinvesting into a larger PV system. This stems from the fact that PV generation cost are higher than the reimbursement for grid export, but lower than PV import cost. Note that the vertical dashed lines at roughly +40kW and -40kW are the electrical grid capacity limits for the discussed building.

The difference in e-Grid interaction between the traditional mobility and the electrical mobility case for the same cost-minimal setting including base technologies plus PV can be seen in Figure 68. The demand peaks are clearly higher in the e-Mobility case and occur during the winter. Also, the surplus

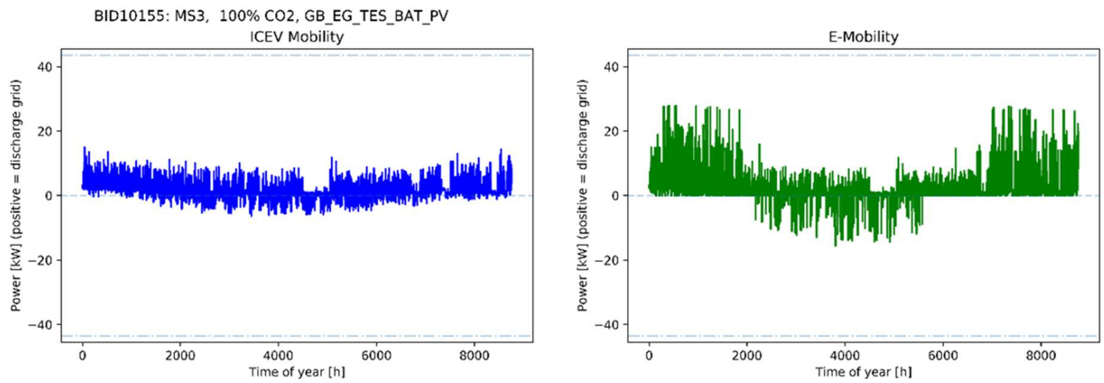

Figure 68: e-Grid exchange comparison between the cost-minimal solution including base + PV technologies for traditional (left) and e-Mobility (right).

generation during summer is larger than in the traditional case. This is due to a larger cost-optimally installed PV system. Overall, one can clearly see the larger winter versus summer difference.

The cost-minimal e-grid exchange in the case of a CHP also being available (see Figure 69) looks quite

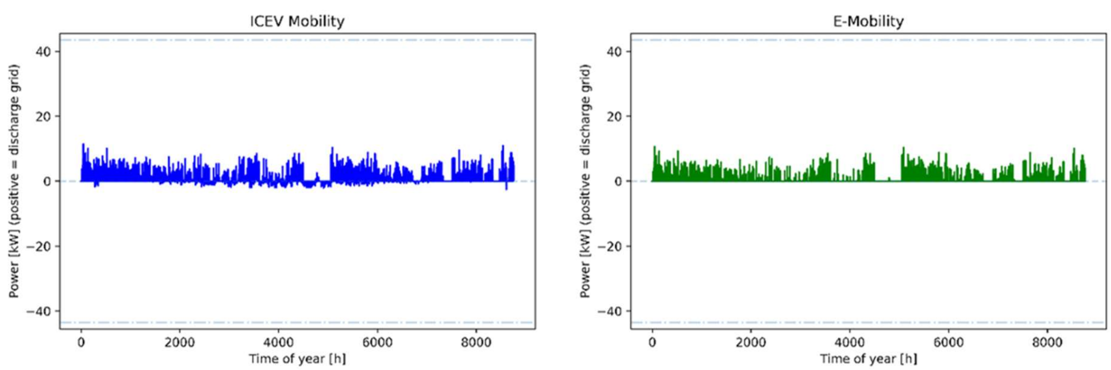

Figure 69: e-Grid exchange comparison between the cost-minimal solution including base + PV + CHP technologies for traditional (left) and e-Mobility (right).

different from the previous case. Here the oversupply of electricity in summer for the traditional mobility case is much less pronounced. This implies a smaller optimally installed PV system. The plot on the right-hand side of the Figure even shows no oversupply during summer. This implies that either no PV system is installed, or all the electricity coming from a rather small PV system can be charged into the EV batteries instead of being exported to the grid.

In the third technology scenario that includes the possibility of installing a heat pump instead of the CHP system (see Figure 70) the e-grid is utilized to a much larger extent. One can see, via the larger oversupply during summer that the installed PV is even larger than in the base + PV technology case. This makes sense since the heat pump, which is installed in the cost-minimal solution, causes additional electricity demand, which in turn is economically more attractively supplied by a PV system than by the grid.

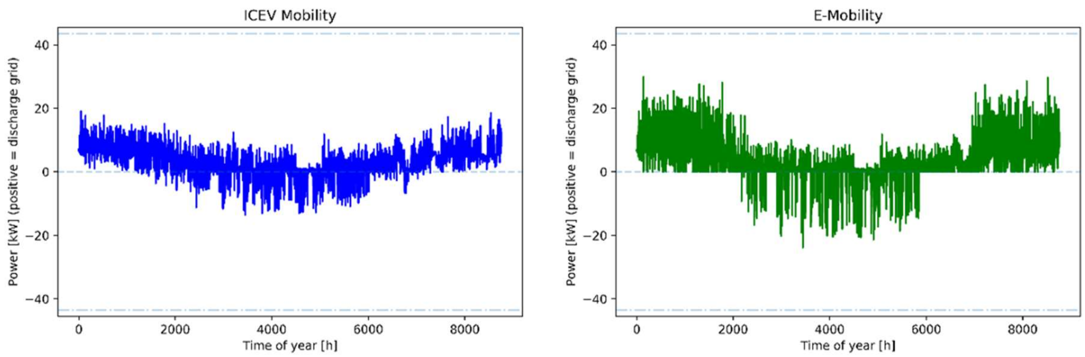

Figure 70: e-Grid exchange comparison between the cost-minimal solution including base + PV + HP technologies for traditional (left) and e-Mobility (right).

The three figures above highlight the importance of technology availability for the way the grid is utilized. Large winter to summer differences as well as high grid dependency from heat pump scenarios during winter can be expected. The installation of a CHP system can largely reduce the grid exports but increases the dependence on gas supply. Moreover, e-Mobility does change the cost-optimal design and hence operation of the energy hub. This can lead to large implications for the grid infrastructure utilization. Therefore, interaction and communication between the asset installing consumers/prosumers and the upstream utility / grid providers is suggested either directly or indirectly via price changes / incentives if the grid utilization reaches critical limits.

1 % margin CO2-minimal Analysis

The next three figures discuss the same impact of e-Mobility and technology availability on the utilization of the electrical grid as before. However, instead of assessing the outcome for the cost-minimal solution, they highlight the power exchange profiles for a near CO_2–minimal scenario.

Figure 71 displays the base + PV technology solution. It becomes clear that the PV system size in this scenario is maximized, since the electricity production from the PV panels is assumed to generate no operational CO_2. Due to the larger demand caused by the EVs the import load peaks are higher in the case of e-Mobility. This is especially pronounced during winter. Another interesting point is the lack of grid export during the early and late winter months. During this time the PV production is fully charged into the batteries of the EVs or the stationary battery, mitigating the need for grid exports.

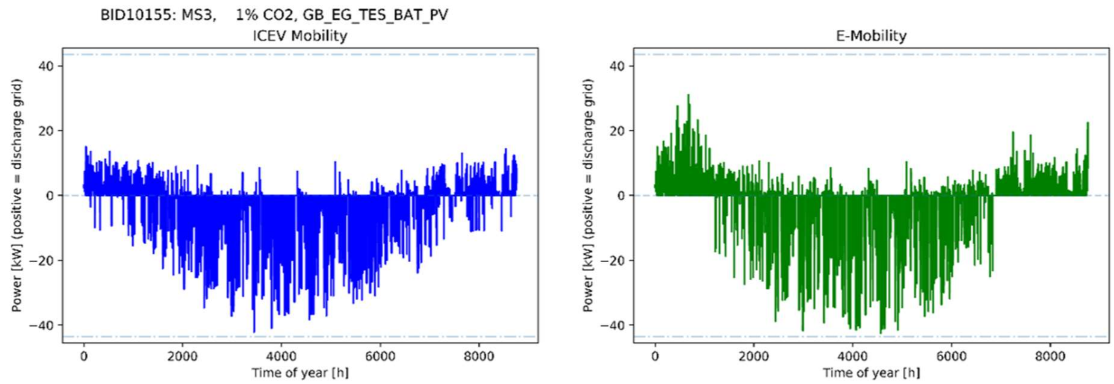

Figure 71: e-Grid exchange comparison between the 1% margin CO_2 –minimum solution including base + PV technologies for traditional (left) and e-Mobility (right).

An additionally available CHP system (see Figure 72), does not change this ecologically constraint optimization as the CHP system cannot provide electricity or heat without emitting operational CO_2 and is hence not installed in this solution.

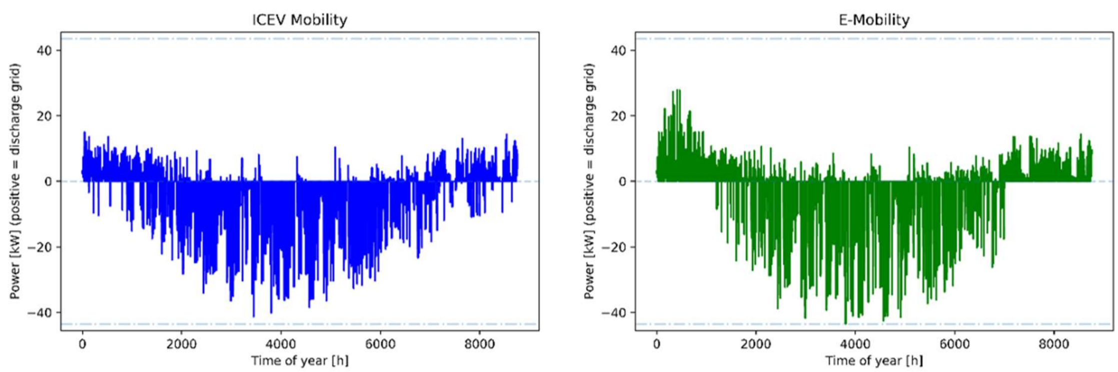

Figure 72: e-Grid exchange comparison between the 1% margin CO_2 –minimum solution including base + PV + CHP technologies for traditional (left) and e-Mobility (right).

Again, the most extreme utilization profile of the electrical grid is created in case of e-Mobility being combined with a heat pump (see Figure 73). When the ecological impact of the operation of the assets is to be reduced, then the load profiles get even harsher than in the previous case including a heat pump under a cost-minimal objective (cf. Figure 70). This is expressed by positive and negative load peaks reaching the capacity limit of the electrical lines during summer and winter respectively.

The pathway of electrification of the mobility as well as the heating sector into the future along with the objective to reduce CO_2 emissions drastically, will cause a large change in the operation of the electrical grid as compared to today’s operation where excessive amounts of heat pumps and EVs are still unimaginable. Even with, or due to, the installation of big solar production capacities the dramatic seasonal change between net demand and oversupply in this scenario make a stable, and dependable grid or alternative local smoothing approaches (like large batteries and CHPP generation) indispensable.

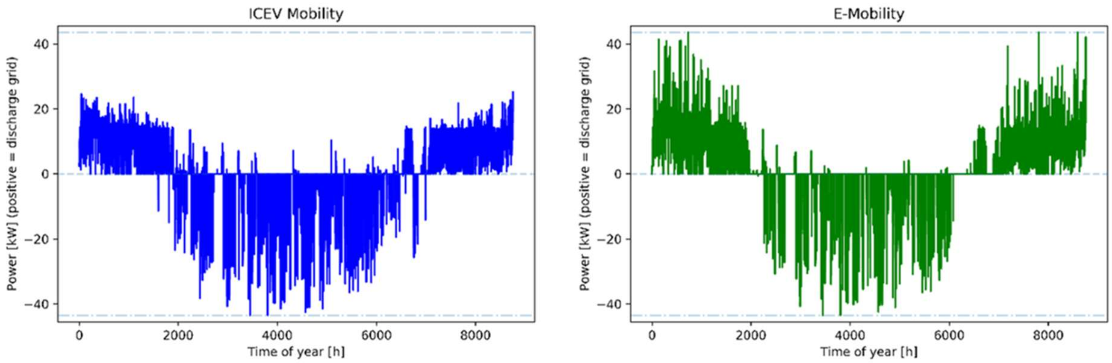

Figure 73: e-Grid exchange comparison between the 1% margin CO2 –minimum solution including base + PV + HP technologies for traditional (left) and e-Mobility (right).

In this section of the report, it becomes clear that ambitious CO_2 reduction goals will cause other technologies to be installed that today's common assets. This will have significant impact on grid operation. A sensible evaluation of the technologies' advantages and disadvantages in todays and the future's energy system is therefore essential to allow a stable, economically feasible yet rapid energy transformation. To some extend this is investigated in the main section of this report in Section 3.4, further work on reducing the impact on the grid is however suggested.

10.3.9 A Neighbourhood and its Energy Exchange Dependence under Varying CO_2 Emission Goals

In this section of the report the sum of the simulated community energy hubs is analysed to identify how a group of 32 buildings, composed of a mix of singles and multi-family buildings, behaves in terms of their energy supply infrastructure dependence. This set of buildings can be seen as a neighbourhood that is supplied by nine decentralized energy system that are supported by the gas and electrical grid infrastructure.

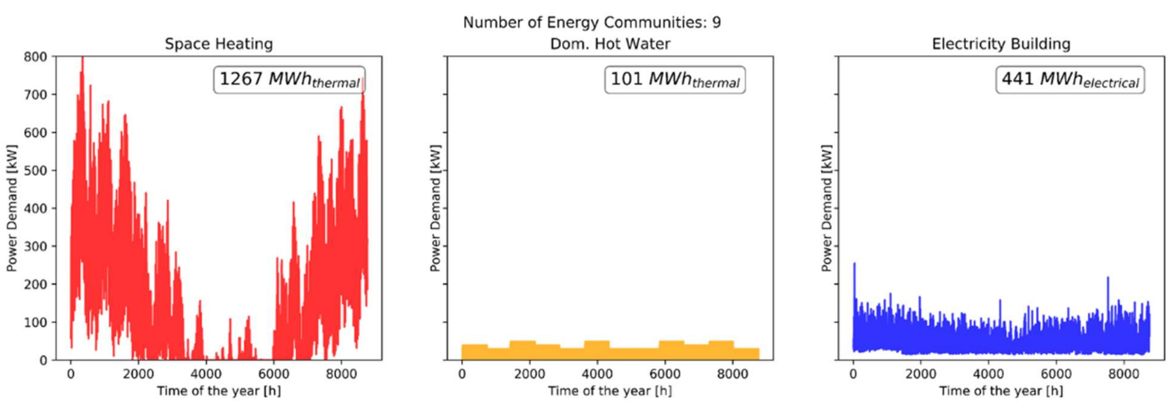

Figure 74: Sum of power demand profiles for Space Heating, Domestic Hot Water and Electricity of all 32 buildings in the neighborhood.

Figure 74 shows the sum of the power demand profiles for all 32 buildings in the neighbourhood over the course of a year. The annual energy demand per demand type is also indicated. Space heating poses the largest energy demand with the largest seasonal variation. Electrical energy demand is the second largest demand type, followed by the domestic hot water demand.

In the left plots of Figure 75 the energy import and export for gas (top) and electricity (bottom) is given in case all energy hubs use standard technologies, namely the gas boiler, the thermal energy storage, and the electrical grid to supply their demands. In the right plots of the figure the energy exchange with the grids for the cost-minimal case, ecologically unconstraint optimization is shown. Here all technologies as used in the energy hub analysis are available. Some effects can be identified:

- The technology-rich case on the right, relies more on gas than the base case. The CHP system offers an inexpensive way to provide electrical and thermal energy.
- Peak gas demands are slightly higher in the technology-rich case. This is in line with the first bullet point. As there is a shift towards gas based CHPPs for cost-optimized solutions.
- Gas imports have higher peaks in summer in the technology-rich case.
- Overall electricity import dependence is much reduced in technology-rich case
- The technology-rich case often exhibits periods of zero net electricity demand, whereas the base technology set exhibits a baseload demand at all times. (CHP supplies electricity on demand and excess PV production can be converted to thermal energy via the heat pump)

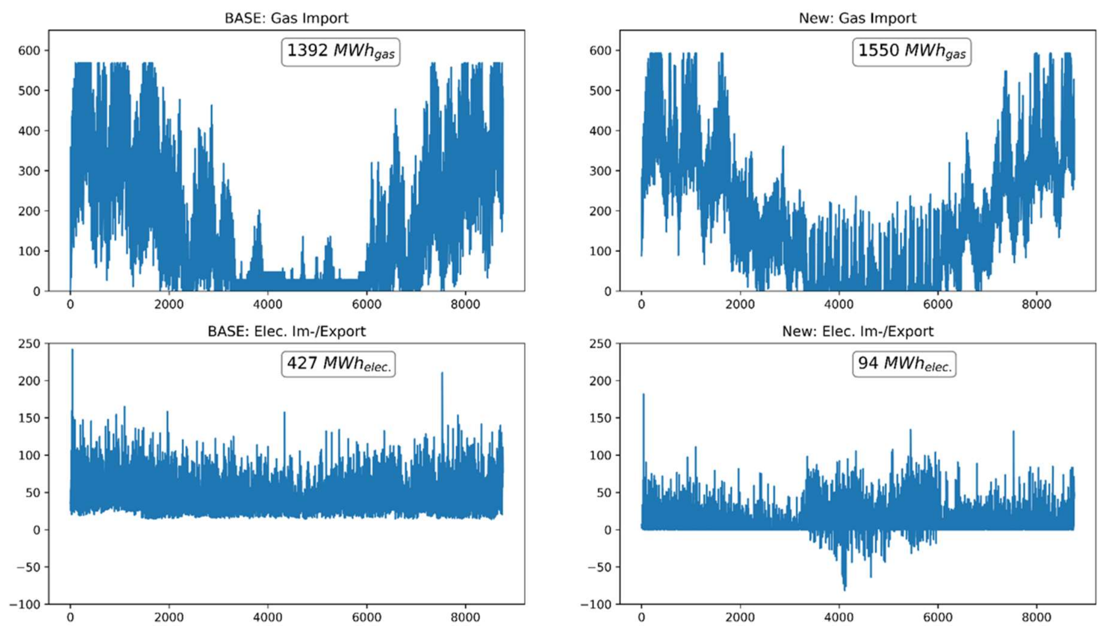

Figure 75: Sum of the energy hubs' gas import (top) and Electricity Import and Export (bottom) over a year for the base technology case (left) and the cost minimal solution with all technologies available. (x-axis in hour, y-axis in kW)

- Electrical imports rise during summer, where the CHP does not operate due to low thermal demand.
- Oversupply from PV production exists during summer in the technology-rich case. In summer thermal demand is low, therefore the conversion from electricity to heat is not a viable option for all PV production.

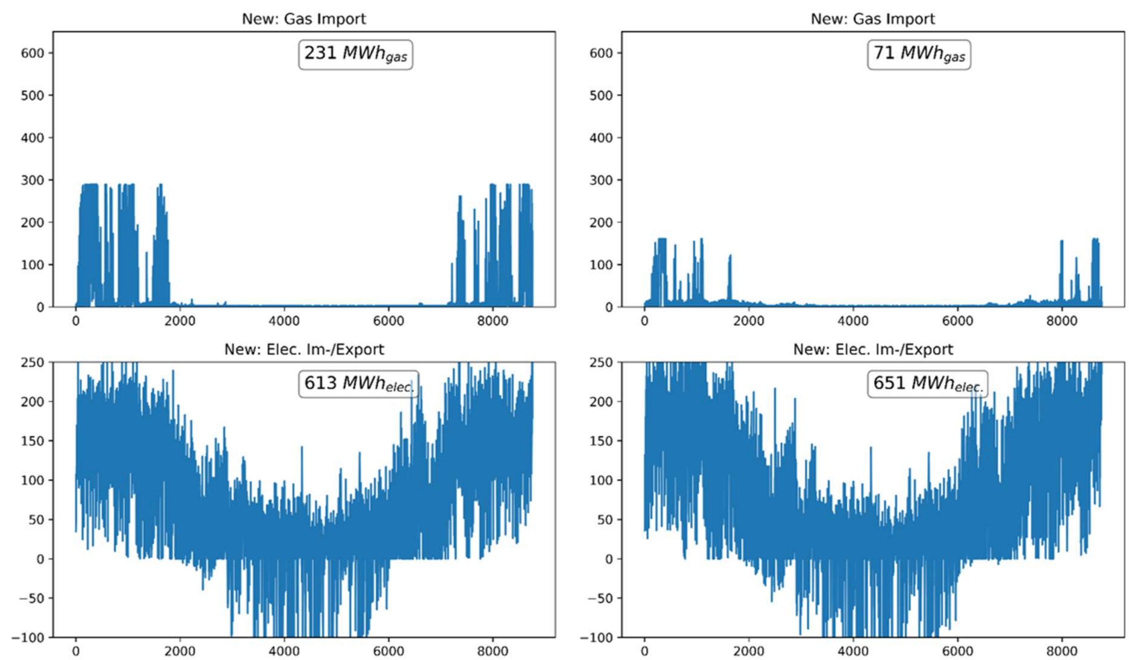

Figure 76: Energy Hubs' grid dependence in a scenario where CO_2 emissions are forced to be reduces by 50% (left) and 85% (right) as compared to the cost-minimal solution

Figure 76 shows the optimal operation of the grid infrastructure in scenarios of a 50% (left) and 85% (right) emission reduction utilization from the cost minimal optimization. Already in the case of a 50% reduction the optimal solution shifts largely away from gas as an energy carrier (see top left plot), towards a large dependence on electricity (see bottom left plot). This trend continues and will place large requirements on the electrical grid infrastructure in a future in which emission reductions are even stricter. The right plot of the figure shows this for an 85% emission reduction utilization from the cost minimal solution. The reduced demand for gas will in future also put stress on the economic viability of the gas infrastructure, as annual gas demand is reduced by a factor of > 20 in the 85% reduction versus minimal cost solution.

The above analysis show that overall, the buildings, despite their variance in terms of size, construction year, number of dwellers face similar technology installation and operation trajectories. In light of the increasing ecological ambitions, we are bound to see a substantial shift in optimal asset selection. Their operation however will substantially impact the grids' typical operational patterns. To mitigate the stress on the grid infrastructure one will be well-advised to steer the transitional developments into directions of less infrastructure impacting alternatives.

10.3.10 Intermediate Conclusions

From the analysis presented in this section of the report it becomes clear that the availability of technologies can have a substantial impact on the optimal design and operational patterns on the energy hubs and the adjacent grid infrastructure. Additionally, the emission reduction ambitions largely define the outcome of the energy hub optimizations and can completely alter the composition of optimal supply systems. For a widespread rollout of these systems, energy systems planners must therefore accommodate for the expected changes by altering the adjacent systems or setting the right incentives to steer the design and operation of local energy assets into mutually beneficial paths.

It is further recognized that the analysis of such optimal energy systems via the described methods offers the opportunity to comparatively evaluate today's and the future's systems from a multitude of perspectives and angles. In doing so, it is important to recognize the crucial aspects to evaluate the systems and advance research in this field towards a holistic approach.

The research in the main section of this report includes the learnings taken from the initial stages of the project and presents solid, yet expandable investigations and insights to hopefully steer and accelerate the joint energy and mobility system transformation.