Modelling & Optimization of Energy Systems

Assessment of building stock impact on global energy system optimization

Master Project

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Abstract

This project falls within the framework of a Master Thesis at the Industrial Processes and Energy Systems Engineering (IPESE) laboratory of Ecole Polytechnique Fédérale de Lausanne (EPFL). With the aim of assessing the building stock impact on global energy system and its sensitivity to renovation and climatic conditions, a tool is designed from three models of energy system, each having a particular scope and interesting potential contribution to the project. The objective is to make it as automatized, independent and adaptable as possible in order to allow any individual working on one of these models to integrate the approach, use different inputs and methods and easily generate results for various conditions.

The tool takes as input a building stock clustering and characterization (Paul Stadler's Database (PSD)) that allows to scale up to the national level the results from individual buildings optimization, performed with a second model (Smart Building Designer (SBD)) under several scenarios and conditions. The resulting options are then integrated into a global energy system optimization model (EnergyScope (ES)). It is then applied to a pre-defined specific case study of Switzerland in 2050 to generate and analyze results under several conditions, in order to understand the building stock behavior and impact within national energy system optimization.

The separate optimization of the building stock, even though limiting the flexibility of the global energy system optimization, allows not only to assess its considerable impact on the national system, but also highlights conflicts of interest between the different scopes as well as the importance of the definition of the different costs. Indeed, the resources costs appear to have a significant impact on the resulting expenditures, emissions and energy mix, but the consideration of the different layers and scales, from individuals to intermediaries, private/public companies and governments, is also crucial. The building stock granularity per typical buildings and geographical regions allows to grasp examples of such disparities, as well as the impact of climatic conditions variation, on the different regions, the total building stock and the national energy system. It also allows the integration of a renovation option, which is analyzed as well and appears to have very little impact on the total building stock. Several sensitivity analysis are performed to assess the considerable impact of resource-specific costs and carbon emissions, as well as the use of several scenario options for the integration of the building stock in the global energy system with a reasonable impact on the computational time.

In the end, the designed tool allows to generate various results to address the research questions and better understand the behavior and impact of building stock within global energy system optimization. And it also leaves room for later improvement such as consideration of district interaction during the separate building stock optimization, or a deeper analysis on climate change with the addition of cooling technologies.

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Acronyms

AAHP (AAHP) Air-Air Heat Pump
AWHP (AWHP) Air-Water Heat Pump
BA (BA) Batteries
BO (BO) Boiler
BS (BS) Building Stock
DHN (DHN) District Heat Network
DHW (DHW) Domestic Hot Water
DW (DW) Domestic Water tank
EH (EH) Electrical Heaters
EPFL (EPFL) Ecole Polytechnique Fédérale de Lausanne
ERA (ERA) Energy Reference Area
ES (ES) EnergyScope
FSO (FSO) Federal Statistical Office
GHI (GHI) Global Horizontal Irradiation
GWP (GWP) Global Warming Potential
HP (HP) Heat Pump
HS (HS) Heat Storage
IPESE (IPESE) Industrial Processes and Energy Systems Engineering
MILP (MILP) Mixed Integer Linear Programming
NG (NG) Natural Gas
PEC (PEC) Primary Energy Consumption
PSD (PSD) Paul Stadler's Database
PV (PV) Photovoltaïc
RegBl (RegBl) Register of Buildings
SBD (SBD) Smart Building Designer
SC (SC) Self-Consumption
SH (SH) Space Heating
SOFC (SOFC) Solid Oxyd Fuel Cell
SS (SS) Self-Sufficiency
TB (TB) Typical Building
TD (TD) Typical Day
TOTEX (TOTEX) Total Expenditures
TS (TS) Thermal Solar

Chapter 1

Introduction

1.1 Problem Statement

In Switzerland, the national building stock (households & commercial buildings) represents the largest consumption of energy (in 2017, 46.3% [1]). It is at stake for important questions and duality between politics role and individuals responsibility, between private and public sectors, between landowner and tenants regarding the sharing of costs for energy consumption and transition. All in all, buildings are an important and thorny part of national energy systems.
Therefore, this study will try to address the following question:

What is the impact of building stock on global energy system optimization

In addition, the project will focus on the potential of renovation to improve its optimization, as well as its sensitivity to climatic conditions. With the aim understanding the stakes and behavior of building stock within wider energy systems optimization, the objective of this study is therefore to see if the integration of separate building stock optimization could improve the nation-wide energy system optimization, while answering the following three sub-questions:

1. What is the impact of building stock on global energy system optimization?
2. What is the impact of renovation on building stock and its weight in the energy system?
3. What is the impact of climatic conditions on the building stock optimization and integration within larger energy system?

To answer them, this work follows the following structure: first, a clear methodology of the combined integration of models, the handling of data throughout the resulting process, as well as the assumptions and considerations will be detailed. Then, the resulting model will be validated by simulating a specific case study chosen according to the validation of the used models. Then, a second case study will be chosen and defined to generate and analyse the results of the optimization and study the impact of the modifications and of the implementation of BS optimization. A sensitivity analysis of the results under several parameters variations will be performed as well, before discussing the limitations of the study and concluding it.

1.2 State of the art

This study focuses on the integration of building stock optimization within a more global nation-wide energy system optimization. It is based on three different models, each having a different focus, scope, set of assumptions and objective. The first one, EnergyScope T.D.s [2], is mainly focused on nation-wide energy systems optimization. Developed first on specific case study of Switzerland, it has then been extended to other European and even non-European countries, and larger scales are currently being studied. It has also been gradually improved to integrate mobility demand and supply (in addition to energy demand encompassing electricity and heating), as well as improving time granularity, passing from monthly basis to hourly basis. The second one, developed within the IPESE lab by Luise Middelhauve, is Smart Building Design (SBD). Mainly focused on building optimization, it has a different scope, scales, costs and variables than the previous one. The available technologies are installed within the buildings, and the remaining energy is imported from the grid (electricity & NG). Even though the first development is single-building oriented, several buildings can be optimized at the same time, and district considerations and interactions are being developed. The last one, developed by Paul Stadler for his PhD thesis *Model-based sizing of building energy systems with renewable sources* [3], hereafter referenced as Paul Stadler's Database (PSD), conducts energy system optimization (with a similar approach to SBD) on building-to-national scale. Unfortunately, the approach has been used as a one-shot study and does not consist of a re-usable tool, with a significant lack of data and files. However, the way the buildings optimization is scaled up to a nation-wide energy system is of interest and represents the main asset that will be used throughout this study: the clustering of the Swiss national building stock.

All in all, each model has pros & cons, different features and scopes (summarized in Table 1.1), but also presents strengths and aspects that could be combined in a powerful approach to make the most of all the three studies. Indeed, the precise and building-specific optimization of SBD, combined with the building stock clustering of PSD, could be an efficient and automatized tool to optimize the whole building stock of Switzerland, before integrating it within the powerful, automated and adaptable tool that is EnergyScope model, modified to consider a set of optimized options of the building stock rather than having a fixed demand and no consideration of geographical and building types disparities.

The table 1.1 summarizes the different features of the three model, as well as their use in the current project structure, which is detailed and explained in Section 2

Table 1.1: Model comparison

Model	**Swiss Energy Scope (SES)**	**Smart Building Design (SBD)**	**Paul Stadler Database (PSD)**
Objective	Nation-scale Energy System Optimization	Building-scale Energy System Optimization	Nation-scale Energy Optimization of Building stock
Use	Global / Second Optimizer	Local / First Optimizer	Building stock clustering model
Scale	National to Continental	Building to District	National
Clustering	Time (*Domínguez-Munoz*)	Time	Time (*Domínguez-Munoz*) & Building-Stock
Optimization	MILP	MILP	MILP
Time Resolution	Hourly	Hourly	Hourly
Programming Language	AMPL	Python + AMPL	-
Input	Annual national energy demand, resource availabilites & technology constraints	Building-specific & geographical characteristics	-
Output	KPIs Nation-scale	KPIs Building- & District-scale	KPIs Building- & Nation-scale

Chapter 2

Methodology

2.1 Objectives & Method

In order to achieve the goal of answering the three main questions enunciated in Section 1, and following what has been introduced in the State of the Art, a tool will be designed based on the available models in order to be able to generate results of nationwide energy system optimization under several variations of the building stock conditions.

The tool will be designed as depicted in Figure 2.1. In order to be able to scale up optimization results of specific buildings to the national building stock, the clustering method and resulting database from Paul Stadler's work (referenced hereafter as PSD) will be extracted and translated into usable input for the SBD model. Then, the latter will be modified to integrate the newly generated input, to optimize each building independently with an additional renovation option, and finally to compile and export the results into usable data for the ES input. These results will consist in a set of scaled optimized options (for different scenarios) for the whole building stock to be selected by ES's Mixed Integer Linear Programming (MILP). Thus, the latter will also be modified to integrate the new input files and select the preferable option for each of the typical building. Finally, and before being able to generate and interpret the results, the new model will be validated with a simulation of a specific case study from past years to be compared with real measured data.

One of the objective set when designing the project structure was to allow ES to select among several scenario options for the Building Stock (BS), instead of having a fixed optimized national demand. It should allow the MILP to select the most preferable option, that may not be the one expected or found by SBD for the same objective, as the BS is part of a larger energy system that is the focus of the second optimization. To go even further with this approach, and in order to make the most of the granularity of the BS clustering, the output from SBD to ES is chosen to be detailed per typical-building.

In line with the project goal, and in order to offer a tool that could be re-used under different conditions, for any region or country (with prior gathering of the required input data and parameters) and that could be easily integrated by people working on any of the used tools, the model will be designed according to the following sub-objectives, or guidelines:

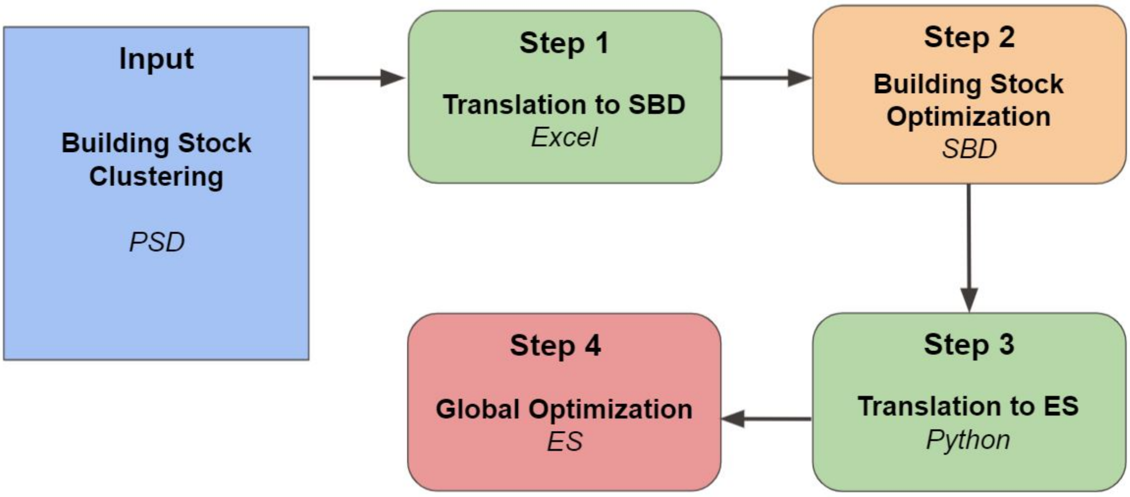


Figure 2.1: Project structure: models integration

1. *Independent*: Modify as little as possible the original models. Create additional files to be easily integrated and used by others on different versions of the used tools.

2. *Automated*: Propose parameters & conditions selection and/or definition in main run files to allow for direct and easy input modifications for various executions of the model without having to change the code.

3. *Adaptable*: The above-mentioned input modifications as well as the clustering, selection and optimization method should be easily changed to study different case studies and conditions.

2.2 Input: PSD - Building stock clustering & database

The general approach starts by extracting from Paul Stadler's thesis the required information to rebuild and use the building stock clustering and depiction he created. As explained before, it results in a set of 105 typical buildings (15 typical buildings × 7 geographical clusters), each having different energy demand, characteristics and representativeness in the national building stock. The aim of this section is to identify and extract the needed data that will then be translated into usable input for SBD.
Before going further, the clustering and indexing of buildings from PSD needs to be explained. As said before, it results in 105 typical buildings, but there are actually 189 buildings characterized in the database. Indeed, the building stock is divided according to different types/indexes that are listed in Table 2.1. The building type describes the use, whether it is a *residential single family house* (resid_sfh), a *residential multiple family house* (resid_mfh) or a multiple-use building , i.e. a building with both households and services. The construction dates are clustered by periods, named after the last year of these periods (e.g. the *2020* construction period holds for the buildings built between 2005 and 2020), while the geographical locations are clustered by typical climates characterized by

a meteorological station city name. Paul Stadler's thesis [3] describes how it has been performed. Finally, as part of the study outcome, all buildings present a renovation option, except for the ones of the last construction period. Therefore, there are:

$$\begin{gathered} 3\ buildings\ use \times 5\ construction\ period\ \times 7\ clusters\ = 105\ typical\ buildings \\ + \\ 3\ buildings\ use\ \times 4\ construction\ period\ \times 7\ clusters\ =\ 84\ renovation\ options \\ = \\ 189\ characterized\ buildings \end{gathered} \tag{2.1}$$

Note that, in this study, Typical Building (TB) will either refer to the 15 or 105 buildings, depending on the context.

Table 2.1: List of parameters describing the set of typical buildings

Type	**Values**
Building Type	{resid_sfh, resid_mfh, mixte}
Construction Period	{1920, 1970, 1980, 2005, 2020}
Cluster/Region	{Bern-Liebefeld, Davos, Disentis, Geneve-Cointrin, Lugano, Piotta, Zuerich-SMA}
Renovation	{Yes, No}

Even though Stadler's wok does not consist in a re-usable tool but rather in a one-shot study with a report describing its methodology and results, a set of files gathering the different inputs, outputs and parameters that compose the dataset is also available. The ones that are useful for this study are listed and described below.

- *heat_demand.csv* : Heat demand per typical building without renovation [15x1]
- *regbl_commune.csv* : Energy Reference Area (ERA) per typical building per commune [15x2294]
- *resid_mfh.csv* : Hourly energy demand (electricity, Domestic Hot Water (DHW), Space Heating (SH)) and occupation of buildings of type "MFH" [24x4]
- *resid_sfh.csv* : Hourly energy demand (electricity, DHW, SH) and occupation of buildings of type "SFH" [24x4]
- *mixte.csv* : Hourly energy demand (electricity, DHW, SH) and occupation of buildings of type "mixte" [24x4]

- *clustering_idx.csv* : List of communes with attributes and cluster [2440x7]
- *clustering_midx.csv* : List of clusters with their name, ID and occurrence [7x3]
- *db_index.csv* : Specific parameters values of characterized buildings [189x7]
- *heidi.csv* : Renovation details and correspondence of typical buildings [105x5]

Note that some parameters values of building types and regions can also be found in tables provided in Paul Stadler's thesis [3]. From these files, a certain number of data is of interest for the current study:

1. *Clustering*: the allocation of communes to a cluster, combined with the estimated ERA of building types per communes, allows to generate the total representative ERA of each typical building.
2. *Building Characteristics*: parameters values of buildings that are type- & age-specific, that will allow to characterize the energy system to be optimized in SBD.
3. *Geographical Cluster CC*: parameters values of buildings that are geographically specific, i.e. linked to the external parameters. Note that the latter (e.g. external temperature or irradiation) are not available from the dataset. However, the thesis shows that different time-clustering have been performed for each region, giving the number of clusters and their medoïd (associated day of the year), but no further details such as the exact objective function or the indexing of all the days of the year.
4. *Renovation*: characteristics of the defined renovation option, actually consisting in enhanced values of building envelope properties (U_h), and heating system supply & return temperatures (T_{so} & T_{ro}), associated with an installation cost.

2.3 Step 1: Tanslation & Extraction to SBD input

2.3.1 SBD input requirements

Before translating all these available data into usable entry parameters for the buildings and regions in SBD, the exact needs and format of the latter tool have to be understood and detailed. From available guidelines, the required parameters for buildings and region definition are listed in Tables 2.2 & 2.3.

It is important to note that the regions (called "Cluster" in SBD) only have time-clustering attributes, in addition to their name. Therefore, it means that each cluster may have its own time-clustering, and that their name will call additional files containing data on weather & external parameters.

Table 2.2: SBD required input for buildings

Name Python	Name AMPL	Unit	Description
Transformer	-	[-]	Grid parameter, transformer responsible for house connection
RoofUse	HouseRoofUse	[-]	Share of roof which can be used
SolarGainF	HouseAeraSolar	[-]	Solar gain (fraction of House area)
Tinto	T_in_0	[°C]	Reference indoor temperature
Ucoef	Uh	[kW/K m2]	Thermal transfer coefficient of the building
category	-	[-]	Building- type (1st digit) and period (2nd digit)
edotel	-	[W/m2]	Specific electric needs
hs_A	HouseAera / ERAh	[m2]	Reference Energetic Area or heated surface
hs_Tro	Th_return_0	[°C]	Heating system return temperature
hs_Tso	Th_supply_0	[°C]	Heating system supply temperature
n_p	-	[cap]	Number of people (float)
qdothw	-	[W/m2]	Specific domestic hotwater demand
aff	-	[-]	Affinity/ building type
EGID	-	[-]	RegBL identifier
floor_n	HouseStory	[-]	Number of floors (stories) of building
Ccoef	HouseCcoef	[Wh/K m2]	Heat capacity of the building
hw_tech	-	-	hot water technology', if installed == 1

Table 2.3: SBD required input for clusters/regions

Parameter	Unit	Description
Name	[-]	Name of the cluster/region. Necessary for data allocation in the code.
Hours	[-]	Number of hours per typical day in the time-clustering specific to the cluster/region.
Days	[-]	Number of typical days & extreme periods in the time-clustering specific to the cluster/region.
Attributes	[-]	Parameters that are affected by the time-clustering, usually external temperature T and irradiation I.

2.3.2 Parameters translation and definitions

Now that the needed parameters, their units and definitions have been clarified, the goal is here to translate PSD data into SBD buildings and cluster parameters, i.e. to find the link between the two, calculate or estimate the ones lacking, and moreover change the structure of 189 characterized buildings into 15 typical buildings, 7 geographical clusters and 1 renovation option per concerned typical building.
This structure is first changed by defining a new index set of typical buildings and by associating all the characterized buildings to a typical building (independently of the region/cluster), as shown in Table 2.4.

Table 2.4: PSD translation into SBD parameters

PSD				SBD	PSD				SBD
Type	**Age**	**Reno**	**ID**	**TB ID**	**Type**	**Age**	**Reno**	**ID**	**TB ID**
resid_sfh	1920	No	4001	1	resid_sfh	1920	Yes	4106	1
resid_sfh	1970	No	4002	2	resid_sfh	1970	Yes	4107	2
resid_sfh	1980	No	4003	3	resid_sfh	1980	Yes	4108	3
resid_sfh	2005	No	4004	4	resid_sfh	2005	Yes	4109	4
resid_sfh	2020	No	4005	5					
resid_mfh	1920	No	4006	6	resid_mfh	1920	Yes	4110	6
resid_mfh	1970	No	4007	7	resid_mfh	1970	Yes	4111	7
resid_mfh	1980	No	4008	8	resid_mfh	1980	Yes	4112	8
resid_mfh	2005	No	4009	9	resid_mfh	2005	Yes	4113	9
resid_mfh	2020	No	4010	10					
mixte	1920	No	4011	11	mixte	1920	Yes	4114	11
mixte	1970	No	4012	12	mixte	1970	Yes	4115	12
mixte	1980	No	4013	13	mixte	1980	Yes	4116	13
mixte	2005	No	4014	14	mixte	2005	Yes	4117	14
mixte	2020	No	4015	15					

Then, all parameters have to be either calculated from PSD values or defined from SBD guidelines when information is missing. This is the case for the following parameters:

- *Roof Use* : chosen as the default value from SBD (calculated from SIA Norms and statistics);
- *Tinto* : chosen as the common value of 20°C;

- *Ccoef* : defined as the default value from SBD (calculated from SIA Norms and statistics);
- *hw_tech* : of which value, even if not precised in PSD, is assumed to be 1 for all buildings
- *Transformer, category, aff, EGID* : as purely informative and not useful here, they are not defined here and left as empty strings.

Then, the following parameters are simply and directly extracted from PSD, and are here classified as specific to the:

- ***Building-type*** : hs_A
- ***Construction period*** : hs_Tro, hs_Tso
- ***Both*** : U_{coef}

Note that all these values (except hs_A) vary with renovation, and are the only ones to do so. Therefore, 6 parameters will be added to all buildings, being:

- ***Renovation availability*** : $renov_{opt}$, a binary parameter;
- ***Optimized parameters*** : $Ucoef_{opt}$, $hs_{Tro_{opt}}$, $hs_{Tso_{opt}}$, which will replace the original values if the renovation is installed by the SBD's MILP;
- ***Renovation's costs*** : $cost_{renov}$ (economical) & gwp_{renov} (environmental)

It is important to note that the environmental impact of renovation gwp_{renov} is not defined in Stadler's work. Yet it was chosen to add it here as an input parameter to allow for later consideration, as it may have a crucial impact on its implementation under GWP-optimization of the system. Finally, some parameters were not clearly defined or given as such in PSD, yet could be estimated and calculated from available values, with some assumptions and approximations. These parameters are:

- *SolarGainF* : defined as the ratio of *VAL_sol* (assumed to be the irradiated surface of the building) and *VAL_sre* (the ERA of the building) in *db_index.csv* from PSD;
- *edotel* & *qdothw* : the data from *resid_sfh.csv*, *resid_mfh.csv* and *mixte.csv* about energy demand are given hourly for a typical day. SBD rather needs a peak or average value to calculate by itself the hourly consumption based on already defined occupancy profiles, and directly averaging the hourly values from PSD seems to give underestimated values of the demand. Thus, it was chosen to rather use annual energy demand for electricity and hot water per building type from Stadler's thesis to estimate the average hourly demand;
- n_p : as this parameter is not given in PSD and is quite informative in SBD, it was chosen to estimate and extrapolate it from the communes population weighted by their ERA share of each typical building; (note that, therefore, *mixte*-type buildings are assumed to have the highest number of occupants because of their higher surface, even if it is not necessarily the case);

- *floor_n* : extrapolated from the Register of Buildings (REGBL) data linking building categories with average ERA and number of floors, scaled with the ERA value of PSD's building types. (See Table 2.5).

Table 2.5: RegBl & PSD building types ERA and floors *(RegBL attributes: GAREA: building footprint (OFS), GASTW: number of overground floors)*

RegBl			PSD		
SIA category	**GAREA** [m^2]	**GASTW** [-]	**Building Type**	**ERA** [m^2]	**Scaled Floors** [-]
Individual housing	120	2	sfh	189	3.15
Collective housing	220	2	mfh	505	4.59
Hotel	350	4	-	-	-
Administration	360	4	-	-	-
Education	430	3	-	-	-
Commercial	360	2	mixte	558	3.1
Depot	170	1	-	-	-

2.3.3 Resulting SBD Input

From all the available data and the assumptions and calculations that were made, all parameters needed by SBD can be generated and are gathered in .csv files to be exported and used as input files by the python interface of SBD, being:

- *Export.csv* : the file containing all the estimated parameters values for each of the 15 typical buildings (Table A.2);
- *Scale.csv* : a file with a double-entry table containing all the scaling factors (based on ERA calculation) depending on the typical building ([1-15]) and cluster ([1-7]) indexes (Table A.1);

2.4 Step 2: SBD - Building Stock Optimization

Now that the most of PSD clustering has been made, and that the resulting data has been used to generate input parameters for building optimization in SBD, the latter can be adapted to perform the required operations. The goal is to integrate the building parameters as well as the geographical and meteorological clustering of Switzerland into the tool (Section 2.4.1), before optimizing each typical building for each cluster and for several scenarios (Section 2.4.2). Then, the results of all optimizations need to be gathered, scaled up and translated into usable input files for ES (Section

2.4.3). In addition, all the above mentioned steps shall be executed by newly created additional files that will call SBD code and functions, so that the model will be modified as little as possible and that this new approach could be used by anyone using SBD, as explained in Section 2.1. Therefore, the coding will be structured as follows:

- *TypicalBuildings.py* : the main file, calling all the other ones below, where the user can define the input parameters and call the desired functions to run the optimization;
- *Clustering.py* : defining the different functions and options to define the building stock as set of typical buildings and clusters;
- *Locations.py* : defining functions to generate meteorological data files for any cluster/region from available weather data and desired time-clustering parameters;
- *Loop.py* : the proper optimization functions, calling the SBD MILP iteratively for each of the typical building, each cluster and each scenario;

2.4.1 Integration of PSD data

First of all, the generated input files must be called and used to extract the needed data for buildings clustering and characterization. Regarding the regional or climatic clusters, additional data on the weather and external parameters shall be integrated, and a specific time-clustering has to be applied to each of them. Finally, the renovation option has to be defined and integrated into the MILP.

Clustering & Typical Buildings

To begin, a function is defined to extract the data from *Export.csv*, to create and write the characterized typical buildings and return it as a list of buildings for optimization input. As for the clusters (or regions), they are simply defined as dictionaries containing their names and number of typical days (as explained before). The remaining needed data will be generated in the next section.
Following the *adaptability* guideline from section 2.1, the *Clustering.py* file defines several functions to create the sets of buildings and clusters. Indeed, there is not only the above mentioned function reading the input file generated from PSD analysis. Another function allows to manually define all buildings and clusters, as well as to select the ones that will be considered in the sets. This is particularly useful to perform optimization on a reduced set of buildings, which is not only interesting for coding & testing but also allows to focus on the behavior of a specific building under several conditions. In addition, it allows to easily and quickly modify any input parameter to study their influence on the optimization results.

Meteorological data & specific Time-Clustering

As mentioned, in order to fully characterize the different regions, meteorological data is needed. More specifically, 5 .dat files are needed per cluster as input by SBD:

- *DRY_frequency* : listing the typical days of the cluster, their associated day of the year, their occurrence and their length in hours (being of 24 for a typical day, 1 for an extreme period);
- *DRY_index* : associating for each of the 8760 hours of the year [1-8760] an hour of the year [1-24] and a typical day index [1-n] (n being the number of typical days, going, in that case, from 6 to 9);
- *DRY_T* : listing the external temperature of each hour of the day for each typical day [24*n x 1];
- *DRY_GHI* : listing the Global Horizontal Irradiation (GHI) of each hour of the day for each typical day [24*n x 1];
- *DRY_timestamp* : detailing the real day of the year (in dd.mm.yyyy format) each typical day corresponds to, in the year the measures were performed. Purely informative.

Again, PSD dataset did not comprise all the needed information to write all these files. Indeed, only the number of typical days and their associated day of the year are given. Therefore, additional meteorological data is needed, and was extracted from Meteonorm.ch data already available on the servers of the IPESE laboratory. The files are providing different measures, such as external temperature and several definitions of irradiation, for all the hours of the year (8760), for a list of cities of Switzerland. Luckily yet not surprisingly, all the regions resulting from PSD clustering are characterized in this dataset.
Therefore, from these meteorological .dat files, the five *DRY_* files can be written, given that a new temporal clustering is performed, with the help of the parameters given by PSD. Unfortunately, as the objective function of the clustering performed by Paul Stadler (even though explicitly inspired by the work of Dominguez-Munos and al. [4]) is not clearly defined. It was thus manually performed by imposing the typical days (number and associated day of the year) and allocating one to each day of the year with square distance defined as :

$$min \sqrt{(\frac{T_{max} - T_{day}}{T_{min}} - \frac{T_{max} - T_{TD}}{T_{min}})^2 + (\frac{GHI_{max} - GHI_{day}}{GHI_{min}} - \frac{GHI_{max} - GHI_{TD}}{GHI_{min}})^2)} \tag{2.2}$$

This approach, quite raw and not a proper optimization, would deserve improvement. Again, regarding the *adaptability* objective, other functions of clustering can be simply defined or even just called here and integrated in the *Locations.py* file. However, it is interesting to note that the frequencies (or occurrences) of Typical Day (TD)s induced by this method are very similar to the ones reported by Paul Stadler in his thesis.

Renovation option as technology

Finally, the last input from PSD to integrate into SBD is the renovation option. As mentioned above, it was chosen to consider it as a technology, that the MILP will choose to install or not (following the modelling of SBD, that is very similar to the ones of PSD [3] and Energy Scope T.D. [2]). It will have a single fixed size, so that the choice of installing it or not will be somehow binary.

The technology would therefore have installation cost and emissions given by the *Export.csv* data. However, all the parameters of the renovation (as well as its availability) have different values, depending on the considered typical building. Therefore, the technology must not only be modified according to it, but also be "switched" on or off. This will be performed in the *Loop.py* file, explained in the following Section.

Regarding its impact, the renovation technology is modifying the properties of the building envelope (U_h) and of the heating system (hs_{Tro}, hs_{Tso}). Unfortunately, these parameters are used in key equations of the model, where the energy demand is estimated and the system designed. Therefore, at this point, it is mandatory to modify one of the core file of the tool. This is performed as follows :

$$\begin{aligned} U_h &= U_{h_{original}} + (U_{h_{opt}} - U_{h_{original}}) * F_{mult}[reno] \\ hs_{Tro} &= hs_{Tro_{original}} + (hs_{Tro_{opt}} - hs_{Tro_{original}}) * F_{mult}[reno] \\ hs_{Tso} &= hs_{Tso_{original}} + (hs_{Tso_{opt}} - hs_{Tso_{original}}) * F_{mult}[reno] \end{aligned} \tag{2.3}$$

where the $F_{mult}[reno]$ variable is the installed size of the technology, which can be either of 0 or 1.

2.4.2 Loop optimization

Then, after having integrated all the input from PSD, the second step is to use the tool for what it is meant for in this study, i.e. for the optimization of the building stock. As mentioned before, the SBD tool is focused on buildings and can either optimize single, multiple buildings or even districts. Here, as the considered buildings are a set of estimations of the most representative occurrences of the national building stock, spread around the country, considering interaction between the buildings would be too approximative. The optimization of a single building considers interaction with the grid, and is mainly limited regarding common installations, share costs and energy and peak demand or other grid parameters. Therefore, it was chosen to perform independent optimization for all typical buildings, and this is why a *Loop.py* file with dedicated function is created. It will therefore conduct a series of optimization (calling the already defined functions of SBD within three nested loops, each going through the sets of typical buildings, clusters and scenarios, leading to a number of iterations:

$$n = n_{tb} \times n_{cl} \times n_s \tag{2.4}$$

An important feature of this function must be, as mentioned in the previous section, the update of the renovation technology, of which costs and parameters, as well as its availability, will depend on the considered TB. Thanks to the loop approach, this is simply done by first checking if the current TB is eligible for renovation (with its binary $renov_{opt}$ parameter), by then updating the technology parameters with the one stored in the TB dictionary, and finally by adding renovation to the set of considered technologies (before removing it at the end of the loop iteration, in order to be able to re-perform the analysis and modification in the next one).

Furthermore, a second script is created to perform Pareto analysis. Based on a duplicate of the first one described above, it differs in the fact that the scenarios and objectives are not iteratively selected within a pre-defined set but rather defined as Pareto points defined for two contradictory objective functions. This second script is the one that will be mainly used in this study.

2.4.3 Output

Once all buildings have been optimized for each regional cluster and each scenario, the results need to be treated and exported to be used as input for EnergyScope. This is Step 3 of the model integration procedure illustrated in Figure 1.1 (Section 2.1), which will be handled by the newly created file *Output.py*, which will be further detailed in the next section.

2.5 Step 3: Translation & Extraction to ES input

In order to reach this objective, the input for EnergyScope first needs to be identified (Section 2.5.1). Then the results from SBD numerous optimizations need to be treated and written in new data files to be later called by the ES model (Section 2.5.2).

2.5.1 ES input requirements

As mentioned in Section 1.2, ES model relies on a MILP coded using the AMPL language, which is based on three types of files:

- *.dat* files: gathering all the parameters declarations and values assignment. ES model contains general *.dat* files that initialize the needed parameters and assign them default values, but also case-study files that will modify these values depending on the country and year considered;
- *.mod* files: where all the variables and governing constraints are defined;
- *.run* files: the ones to execute, that call the different *.dat* & *.mod* files to design the MILP and optimize the energy system. This is usually where the output display is also defined.

Regarding this, ES will require modifications on each of these type of files, but the ones that are of concern here are *.dat* files. Indeed, the model will later be adapted with the needed constraints, variables and equations to integrate the selection of optimized buildings (Section 2.6). The results from SBD will then be integrated within *.dat* files that will assign to parameters (specific to this study and pre-defined in *.mod* files) their updated values from the last SBD optimization. Note that these *.dat* files will be set to be systematically called by the main *general.run* file (executing the optimization), while the *Output.py* functions will leave the user the choice to either create new files and/or overwrite them within the ES at the end of the SBD execution. Thus, the whole process can be done in almost one execution, or several iterations of the SBD step can be done to create an optimized BS dataset for different conditions and scenarios.
Then from the MILP modelling of ES [2], three types of parameters need to be extracted from SBD in order to characterize the set of optimized BS options:

- ***Annual data*** : gathering the economic and environmental costs of each optimized building option, as well as the installation of PV panels and renovation (that are of particular interest here, and/or constrained). Note that only the installation costs and emissions (as well as replacement costs) are considered here, as the operational ones are defined as a function of the resources consumption;

- ***Time-dependent data*** : the hourly resources (electricity & NG) consumption and production of the buildings, considered by the model as black boxes with fixed costs that are interacting with the grid only through these parameters;

- ***Additional data*** : parameters that are not required to perform the ES optimization, but that may be interesting for results interpretation and/or for scenario constraints on the building stock selection conditions. For now, it actually contains technologies installed sizes.

2.5.2 Translation of SBD results

Now that the needed input for ES has been identified, the handling of SBD results can be defined. The *Output.py* functions will perform their extraction and treatment as follows:

1. ***Aggregation*** : reading the optimization results of all iterations of *Loop.py*, extracting the desired variables values and gathering them in nested dictionaries (with typical building, cluster and scenarios and input indexes);

2. ***Scaling*** : scaling up the gathered results by multiplying them with the values defined from PSD and gathered in *Scales.csv*, as well as adapting the units to the definitions of ES;

3. ***Typical Days translation*** : as some variables are time-dependent, and as all regional clusters have their own time-clustering, that differ from the one of ES, they all need to be aligned. This is quite roughly done by assigning to each typical day of each cluster an ES TD, and adapting the values of the time-dependent parameters;

4. ***Output files writing*** : creating 5 different *.dat* files (1 for the annual data, 1 for the additional data, and 3 (one for each) for the time-dependent parameters, being Elec_demand, NG_demand & Elec_supply), writing the treated results in the required AMPL format and saving them.

About the *Typical Days translation*, it should be noted that the method used is quite limited. Indeed, the association between the ones of regional clusters and the ones of ES was performed based on the days of the year rather than on GHI. This decision is supported by the need for ES typical days to be common to the whole Swiss building stock (to take into account regional disparities). If based on external parameters, the pairing may induce differences in the represented typical days of regions, even with the use of square distances and incremental temperatures and irradiation. However, it limits the representativeness and spread of the different TDs of each cluster, as they are in the end not all associated to an ES TD. Thus, the energy demand of regions may be the same over several typical days in EnergyScope, which would have been the case anyway as they are more numerous than the ones of PSD clustered regions, but maybe less consequently. This represent another limitation of the current approach, which would deserve potential later improvement and will be discussed in Section 4.

It is important to note as well that this step is actually the most time-consuming one, as it represents 80% of the total computational time, which is, in SBD and for a run over 15 TBs, 7 clusters and 10 scenarios, about 7h30. This aspect presents considerable potential improvement as it is mainly caused by the use of python lists & dictionaries to handle the results, that are inspected and modified within loops, browsing each time over the full set of results until it finds the correct indexes and values. This would be more efficient using panda's dataframes for example.

2.6 Step 4: ES - B.S. integration & national optimization

Once the national building stock has been modelled and optimized for several scenarios, it can be integrated to ES MILP. This last step of the project structure may be described in two parts: first, the new input parameters need to be correctly defined and called, as well as the other dependent sets, parameters and variables (Section 2.6.1). Then, as the building stock will not be considered as a fixed demand but rather a set of potential configurations that the MILP may select, some new governing constraints need to be defined and existing ones, like the energy balances and cost calculation, need to be adapted (Section 2.6.2). The approach and execution of this step was largely inspired by the work of Jonas Schnidrig studying the integration of PSD data into ES.

2.6.1 Input data

As explained in Section 2.5.1, the extracted input parameters from SBD were defined and written in 4 *.dat* files. Before defining and initializing them in the AMPL model, the sets gathering all their subscripts values must be defined. The parameters describing the demand and supply represented by SBD input must be removed as well.

Sectors demand & new sets

In the current version of EnergyScope MILP [2], the energy and mobility demand are considered as fixed input parameters, defined for 4 different sectors: *HOUSEHOLDS*, *SERVICES*, *INDUSTRY* and *TRANSPORT*. The optimization program then aims at matching the demand by installing pre-defined technologies, whether they are large plants, industrial- or building-sized (or mobility technologies). According to PSD building stock clustering (encompassing single & multiple family-houses as well as mixte-use buildings), the demand from *HOUSEHOLDS* and *SERVICES* must then be set to 0. This will avoid duplicating the total demand with the newly integrated inputs as well as the potential installation of decentralized technologies within buildings.

Then, as the building stock is not defined as a fixed national demand but rather as a set of scenario options per typical building, two new sets of indexes need to be defined to then create the input parameters. *BUILDINGS* and *SCENARIOS* will thus be ordered sets of indexes going respectively from 1 to the number of typical days *N_TB* and from 0 to the number of scenarios *N_scen*. The two numbers are defined as parameters and will be updated by the input files from SBD, to allow for consideration of different BS clustering and sets of scenario options.

```
param N_TB > 0 default 1;
param N_scen >= 0 default 1;
set BUILDINGS ordered := 1 .. N_TB;
set SCENARIOS ordered := 0 .. N_scen;
```

One would notice that the notion of regional clusters has disappeared at this point. Indeed, for ease and more direct consideration of buildings, the set of 15 typical buildings × 7 clusters was moved into a set of 105 typical buildings during the translation process, as the regional granularity is not of concern anymore, except for the interpretation of results.

Time-independent parameters

Then, from the input file *Annuals.dat* from SBD, the installation cost $c_{inv_{reno}}$ and CO_2 emissions $gwp_{constr_{reno}}$, the replacement cost $c_{rep_{reno}}$, and the installation of PV panels PVA_{reno} and of renovation option RE_{reno} for the whole building stock are actualized. They then need to be defined as follows:

```
# All parameters are [10*105] 2D matrices
param c_inv_reno {SCENARIOS,BUILDINGS} >= 0 default 0;  #[MioCHF]
param gwp_constr_reno {SCENARIOS,BUILDINGS} >= 0 default 0; #[ktCO2]
param c_rep_reno {SCENARIOS,BUILDINGS} >= 0 default 0; #[MioCHF]
param PVA_reno {SCENARIOS,BUILDINGS} >= 0 default 0;  #[GW]
param RE_reno {SCENARIOS,BUILDINGS} >= 0 default 0;   #[-]
```

Time-dependent parameters

The time-dependent parameters (actualized by their own *.dat* files, which are named after them), i.e. the electricity demand *Elec_plus_reno*, NG demand *Gas_reno* and electricity supply (exceeding production) *Elec_minus_reno*, need to be defined as well, as follows:

```
# All parameters are [105*10*24*12] 4D matrices in [GWh]
param Gas_reno {BUILDINGS,SCENARIOS,HOURS,TYPICAL_DAYS} >= 0 default 0;
param Elec_plus_reno {BUILDINGS,SCENARIOS,HOURS,TYPICAL_DAYS} >= 0 default 0;
param Elec_minus_reno {BUILDINGS,SCENARIOS,HOURS,TYPICAL_DAYS} >= 0 default 0;
```

It is important to note that, as the scope varies from building oriented to nation-scale between SBD and ES, the energy & resources flows are not always defined in the same way or direction, as well as their costs. This will be further investigated and discussed in Section 3.4.1, yet the selling price of electricity was therefore not defined in ES and was therefore defined from a new parameter, calculated from the default values of SBD. $f_{elec_{sell}}$ is therefore the coefficient factor to get the electricity selling price from the purchasing price. Note that, depending on further discussions and considerations, this value could easily be modified.

```
param f_elec_sell >= 0 default 0.3;
```

2.6.2 MILP model modifications

In addition to the input parameters from SBD, other new parameters, variables and constraints need to be defined in the general *.mod* file of ES.

Additional dependent parameters

In addition to the already introduced parameters, the values of which are defined from the SBD input, there are two other parameters that are defined and calculated from others. These are the operational expenditures $c_{op_{reno}}$ and emissions $gwp_{op_{reno}}$ of each typical building. Contrarily to the other operational costs and GWP within the model, they are not defined as variables, as they are fully defined by the fixed values of resources demand and supply of the buildings. They were integrated as such and not directly imported from SBD for reasons of concordance with the rest of the calculations as well as to allow to decide on the values of the specific costs and emissions of the resources, that are here kept as defined by the ES model, but could easily be modified for later analysis. These two parameters are calculated as shown below:

```
param c_op_reno {b in BUILDINGS,s in SCENARIOS} :=
sum {t in PERIODS, h in HOUR_OF_PERIOD[t], td in TYPICAL_DAY_OF_PERIOD[t]} (
    (c_op ["ELECTRICITY"] * Elec_plus_reno [b,s,h,td]
    - c_op ["ELECTRICITY"] * f_elec_sell * Elec_minus_reno [b,s,h,td]
    + c_op ["NG"] * Gas_reno[b,s,h,td]) * t_op [h,td]);

param gwp_op_reno {b in BUILDINGS,s in SCENARIOS} :=
sum{t in PERIODS, h in HOUR_OF_PERIOD[t], td in TYPICAL_DAY_OF_PERIOD[t]} (
    (gwp_op["ELECTRICITY"]*Elec_plus_reno[b,s,h,td]
    + gwp_op["NG"]*Gas_reno[b,s,h,td]) * t_op [h,td]);
```

Building stock variables

First, all the variables need to be initialized. First, and most importantly, the decision variable $f_{s_{ID}}$, defining which scenario will be considered for each building. At first, it was considered to be a binary variable, to force the installation of only one scenario option per typical building. However, it was decided to relax this constraint, as it was considerably slowing down the MILP and complicating the optimization, and as typical buildings are not actual buildings but rather a set of thousands of buildings spread across the country, that could therefore be differently optimized. Moreover, the results will later show that, most of the time, the MILP sets by itself integer values of $f_{s_{ID}}$.
Then, there are several variables that are not decisional per se, but rather intermediate variables for calculations. They are either economic, as for the operational ($C_{op_{reno}}$), investment ($C_{inv_{reno}}$) and total (C_{reno}) expenditures of the entire building stock, or environmental, as for its operational ($GWP_{op_{reno}}$), construction ($GWP_{constr_{reno}}$) and total (GWP_{reno}) CO_2 emissions. These variables will be calculated based on the selection of the scenario options per building (i.e. the values of $f_{s_{ID}}$), and will then be integrated in the expenditures and emissions of the global energy system. Details of the calculations are given in Annex (Section A.2)

```
# Decision variable
var f_s_ID {BUILDINGS,SCENARIOS} >=0;
# Economic calculations
var C_op_reno >=0;
var C_inv_reno >= 0;
var C_reno >= 0;
# CO2 emissions calculations
var GWP_op_reno >=0;
var GWP_constr_reno >=0;
var GWP_reno >= 0;
```

Governing constraints

Then, and in order to really integrate this building stock depiction and selection of options, new governing constraints have to be defined and modifications have to be made to the existing ones, that shall now consider the independent impact of building stock.
New constraints have already been mentioned before, for the calculation of economic and environmental variables of the whole building stock (Section A.2. However, they are all based on the scenario selection per building, that is governed by the following equation, imposing this attribution:

```
subject to f_s_ID_constraint{b in BUILDINGS}:
   sum {s in SCENARIOS} f_s_ID[b,s] = 1;
```

Then, existing constraints (or equations) must be modified to take into account the building stock. First, the layer balance equation, equalizing the supply and demand of all resources, is now complemented with the resource flows of electricity and natural gas from the whole building stock (i.e. for all selected scenarios per typical buildings). A more straight-forward modification is the one on the constraints calculating the total cost and emissions of the global energy system, where the total cost C_{reno} and the total emissions GWP_{reno} of the entire building stock just need to be added to the already defined sum. Finally, an important equation in ES model is the limitation of the photovoltaïc potential. Indeed, as this renewable source of energy is highly volatile and sensitive to weather variations, and as energy storage technologies are still somehow at an early stage development, the total installation of PV panels shall be limited for energy security reasons and planning. Therefore, the installed size of PV from the selected buildings scenarios is added to the PV technology from ES.

```
subject to PV_potential:
    f_max["PV"] * c_p["PV"] >= F_Mult["PV"] + sum{s in SCENARIOS,b in
        BUILDINGS}(PVA_reno[s,b]*f_s_ID[b,s]);
```

2.7 Validation - Swiss 2017 Case Study

The methodology and the whole structure having been modelled and detailed, and before being able to generate and analyze the results, the designed model shall be validated with the simulation of a specific case-study and comparison of results with real-world measures. The choice of the case-study is motivated by the scope of the current study (Switzerland), the already available data in the ES model (general European data and the case studies of France & Germany in 2017 and 2050) and the validation case study and approach that were the ones of the design of EnergyScope T.D.s [2] (Switzerland 2011).

Therefore, the case of Switzerland in 2017 is retained for the current validation, and the model will be assessed on its ability to reproduce the conditions (primary energy consumption, technologies production & installation as well GWP) of the energy system of Switzerland in 2017, for which much data is available from the Federal Statistical Office (FSO) [1][5][6][7]. Not all the energy production and installed power are characterized in these reports, so the model will still have some flexibility to reproduce the energy system and will not be able to do it perfectly then. Still, the concerned data is compared in Table 2.6.

Note that, for this step, the contribution of the building stock is not imported from SBD, but rather put back as a fixed demand in the ES model. Indeed, the data is nation-wide and does not have the building granularity this study is imposing. Moreover, SBD is an optimization model with no fixed demand as input but more complex energy balance and consumption profiles estimation. It would thus be very complicated -yet possible- to fix the installed power per house and calculate the building properties from measured demand, while representing the building stock as a single building to optimize and then scale to the total ERA of Switzerland.

Table 2.6: Model validation: MILP model output vs. actual 2017 values for the Swiss energy system.

		2017	MILP	Δ	Δ_{rel}	Units
Primary Energy Conversion	Elec. Imp.	36.50	36.50	0.00	0.00%	TWh
	Wood	11.86	9.56	2.30	19.41%	TWh
	Coal	1.28	1.28	0.00	-0.11%	TWh
	Uranium	59.09	57.97	1.12	1.89%	TWh
	Waste	16.90	6.81	10.10	59.73%	TWh
	Elec. Exp.	30.95	30.95	0.00	0.00%	TWh
	Other renew.	10.11	12.29	-2.18	-21.59%	TWh
	(Wind+Solar+Geo)					
	Hydro	36.67	36.67	0.00	0.00%	TWh
Technologies output	Hydro Dam	16.56	19.51	-2.95	-17.79%	TWh
	Hydro River	15.95	17.16	-1.21	-7.62%	TWh
	Nuclear	19.50	21.45	-1.95	-10.00%	TWh
	Wind	0.13	0.14	-0.01	-4.26%	TWh
	PV	1.68	1.87	-0.18	-10.90%	TWh
	TS	0.70	1.15	-0.46	-65.68%	TWh
	Waste	5.58	5.58	0.00	0.00%	TWh
Technologies installed sizes	Hydro Dam	5.54	10.01	-4.47	-80.71%	GW
	Hydro River	4.26	4.26	0.00	-0.01%	GW
	Nuclear	2.88	2.88	0.00	0.00%	GW
	Wind	0.08	0.09	-0.01	-19.68%	GW
	PV	1.90	1.90	0.00	0.00%	GW
	TS	1.18	1.18	0.00	0.00%	GW
	Waste	0.42	0.41	0.01	3.10%	GW
GHG emission	Total (All gases)	47.98	47.98	0.00	0.00%	MtCO2

Globally, the results are quite satisfying. The parameters with strict constraints are quite evident, as they present no variation between the model and the past year measures. Some technologies-resources duos (like waste and waste incinerators, nuclear power plants & uranium, hydro primary energy & hydro dams, etc.) present noticeable differences, either on the Primary Energy Consumption (PEC), the energy generated by technologies, or their installed size, depending on the applied constraints. This is surely due to differences in definitions of energy flows & technologies efficiencies. For example, in ES model, renewable energy technologies such as hydro dams & wind turbines directly convert PEC into electricity with no losses, while the data from FSO surely does not give the same definition of final PEC, and considers the accumulation pumpage power of hydro dams separately. This is why, when imposing a fixed PEC, the installed size is higher than expected, and reciprocally. The approximation induced by the time-clustering (in 12 T.D.s) inherent to the ES model may also have an impact on the simulation.

Much more consequent differences are noticed for the Heat Pump (HP) and the heat generation from renewable sources. This is induced by the above-mentioned difference in FSO data between the estimated total energy demand (about 264TWh) and the energy production from technologies (about 154 TWh) that are not all characterized. Only the production and installed sizes from the ones displayed in the table are reported, and categories of technologies may sometimes be vague (such as heat generation from fossil fuels). These huge differences are therefore caused by the MILP trying to match the energy demand, with too many degrees of freedom. In addition, some differences in terms of definition of PEC and consideration of how the energy entering the different sectors (households, services, industry & transports) may have led to an over-estimated demand set in ES. There might as well have been a confusion between electrical & thermal power and energy concerning Heat Pumps. In the end, the validation seems quite incomplete and some additional work should be done on the estimation and characterization of the 2017 Swiss case study in order to fully constrain the model and have a robust simulation. However, one can witness the satisfying simulation of the correctly constrained parameters, and as the validation of the ES model has already been performed in the past [2] with more detailed data, the current model validation is judged sufficiently satisfying to proceed to the results generation and interpretation.

Chapter 3

Results

3.1 General - Swiss 2050 Case Study

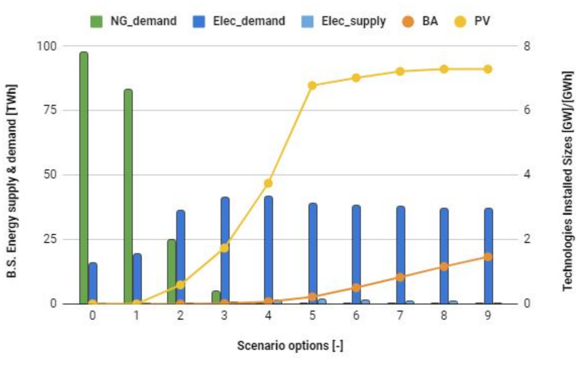
3.1.1 Case Study: Swiss 2050

Similarly as for the validation, the conditions (expected demand, production and specific parameters such as costs, efficiencies and carbon intensities) have to be defined for the desired case study.
The current version of ES comprises data for the case studies of France and Germany, for 2017 & 2050. The parameters values modification are defined in a single *.dat* file per case study, while all the potential additional constraints are gathered in a same *scenarios.mod* file. The original *general_param.dat* file defines all the parameters and initializes them with default values that seem quite generic (in comparison with the values modifications from the different case studies). The Switzerland 2050 data are extracted from the files from G. Limpens work on *Energy Scope T.D.* [2]. Note however that some estimations and values may be missing and left as default, as modifications have been applied to the ES model since Limpens' version.
The resulting variables values that will be displayed hereafter and discussed in the following section are directly generated with the AMPL environment of ES. Indeed, several variables and constraints have been defined and added to additional *.dat* & *.mod* files in order to generate a systemic display, in addition to the costs, emissions and resource production & consumption of the Swiss Energy System and the building stock, of additional parameters that may be interesting for the study. For example, it includes the scenario selection (number of typical buildings per scenario) optimized by the MILP, the installed sizes of technologies from SBD for the whole building stock, as well the share of renovated buildings. In order to have an insight on the behaviour of the clustered regions and the climate impact on the building stock, all these variables are displayed as well as per geographical cluster defined by PSD.

3.1.2 Results

Hereby are displayed the results of the separate building stock optimization and later integration in the Swiss national energy system optimization.
When implemented into ES, the building stock consists in a set of 10 scenario options, defined as pareto points between Total Expenditures (TOTEX) and Total Global Warming Potential (GWP) optimization objectives. The building-granularity of the method leads to a set of 10 options, not only for the building stock but also for each of the 105 typical buildings, which are individually optimized by the MILP of ES. Therefore, at the end of the whole process, the building stock is fully characterized by one single option. However, it is possible to display and analyse its variation under the 10 scenarios directly from SBD output, in order to understand its behavior and characteristics.

Below, one can witness this variation from TOTEX- (scenario 0) to GWP-optimization (scenario 9) in Figure 3.1. The demand for NG drastically decreases while the reliance on electricity increases. Indeed, its demand rises and stabilizes after scenario 5, while PV panels are rapidly deployed as well as Batteries (BA). In parallel, electricity demand considerably increases until scenario 4, and then slightly decreases before stabilizing. Similarly, electricity supply to the grid, which is always relatively low compared to the energy demand, slowly increases until scenario 5, before it keeps decreasing. The second graph of Figure 3.1 displays two additional performance indicators that are Self-Consumption (SC) & Self-Sufficiency (SS). The first one represents the capacity of the system to directly use (and consume) the electricity it produces (rather than selling it and injecting it into the grid), while the latter indicates the share of electricity demand that is addressed by local production. The self-consumption significantly increases in parallel to the deployment of PV until reaching 99.6%, while the self-sufficiency progresses more slowly and remains below 25%.



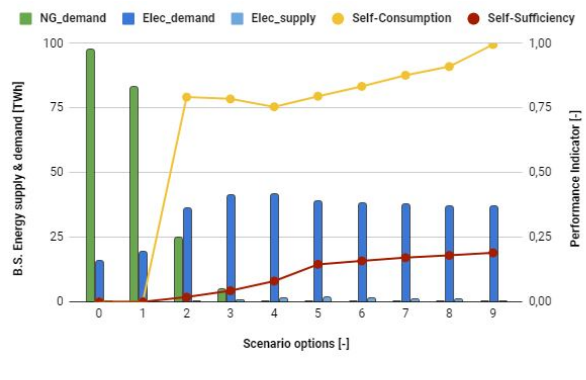


Figure 3.1: Self-consumption & Self-sufficiency of the building stock for the 10 scenarios, compared with its energy demand and production and the installed capacity of PV-panels and batteries (BA)

Then, when implemented into ES and once all scenario options are selected for each building and optimized along with the global energy system by the MILP, the building stock is fixed and fully characterized. The resulting parameters are displayed hereafter, starting with the economical and environmental depiction of the whole building stock (Figures 3.2). Its operational and investment expenditures ($C_{op_{reno}}$ & $C_{inv_{reno}}$) as well as the operational and construction emissions ($GWP_{op_{reno}}$ & $GWP_{constr_{reno}}$) are detailed for each of the two optimization objectives that were used when executing the MILP, being TOTEX and GWP.

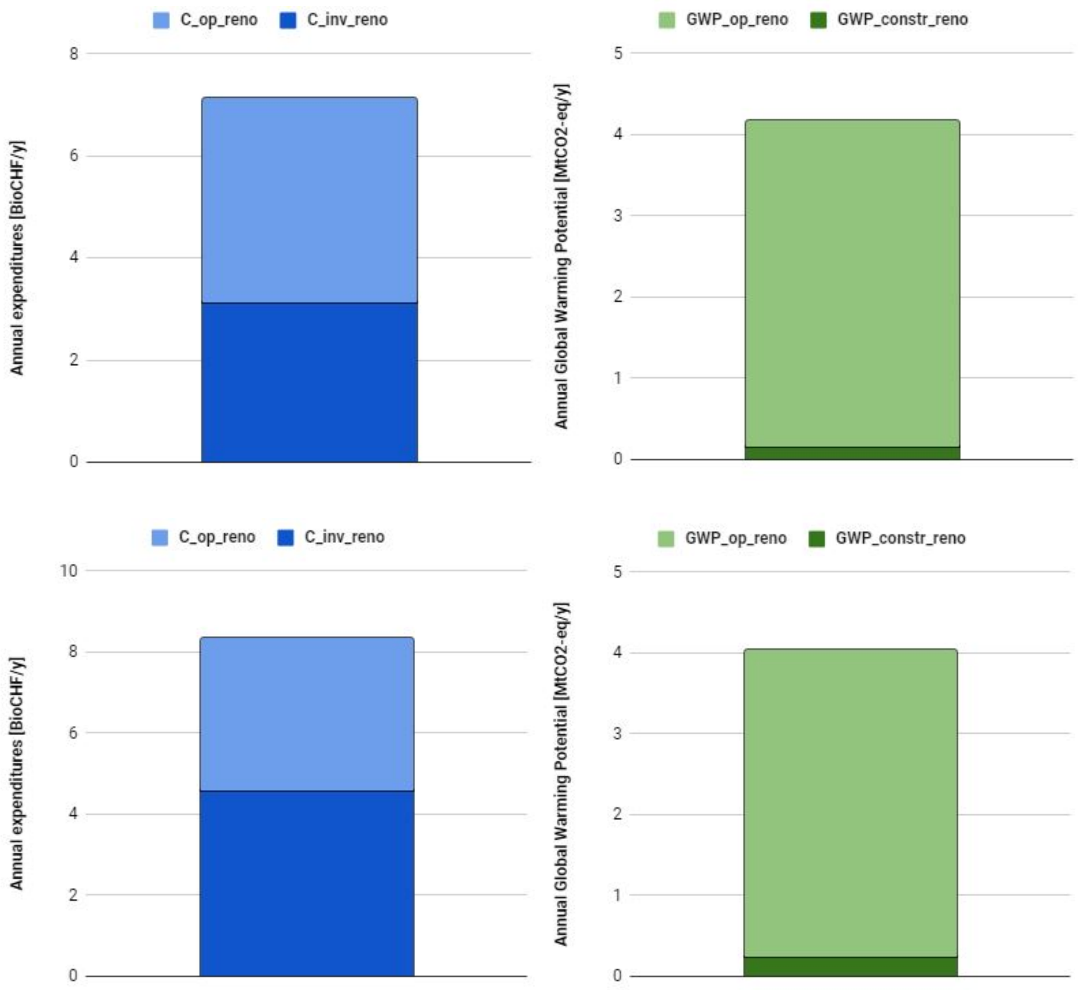


Figure 3.2: Costs (left hand-side) & emissions (right hand-side) of the building stock under TOTEX (top) and GWP (bottom) optimization

These figures show the important share of operational costs and emissions, that are both lowered with the GWP objective, as well as the little variation of the total cost and the even smaller one for the total emissions between the two objectives.

Figure 3.3 illustrates the representativeness of the building stock into the national energy system, with regard to the other domains (Industry (Ind.), Mobility (Mob.), Power Plants (Plt.) and Infrastructures (Infra.)). It shows that, under TOTEX-optimization, it represents a small share of the global system expenditures (25.8%) and even smaller of the total emissions (21.1%). Under GWP-optimization, it however represents a negligible part of the system total cost (0.4%) but induces most of the carbon emissions (72.3%)!

First, one can observe that the building stock respectively represents 25.8% and 21.1% of the total cost and carbon emissions of the Swiss Energy system, under Total Cost (TOTEX) optimization, and that these shares represent 0.4% and 72.3% under Total Emissions (GWP) optimization.

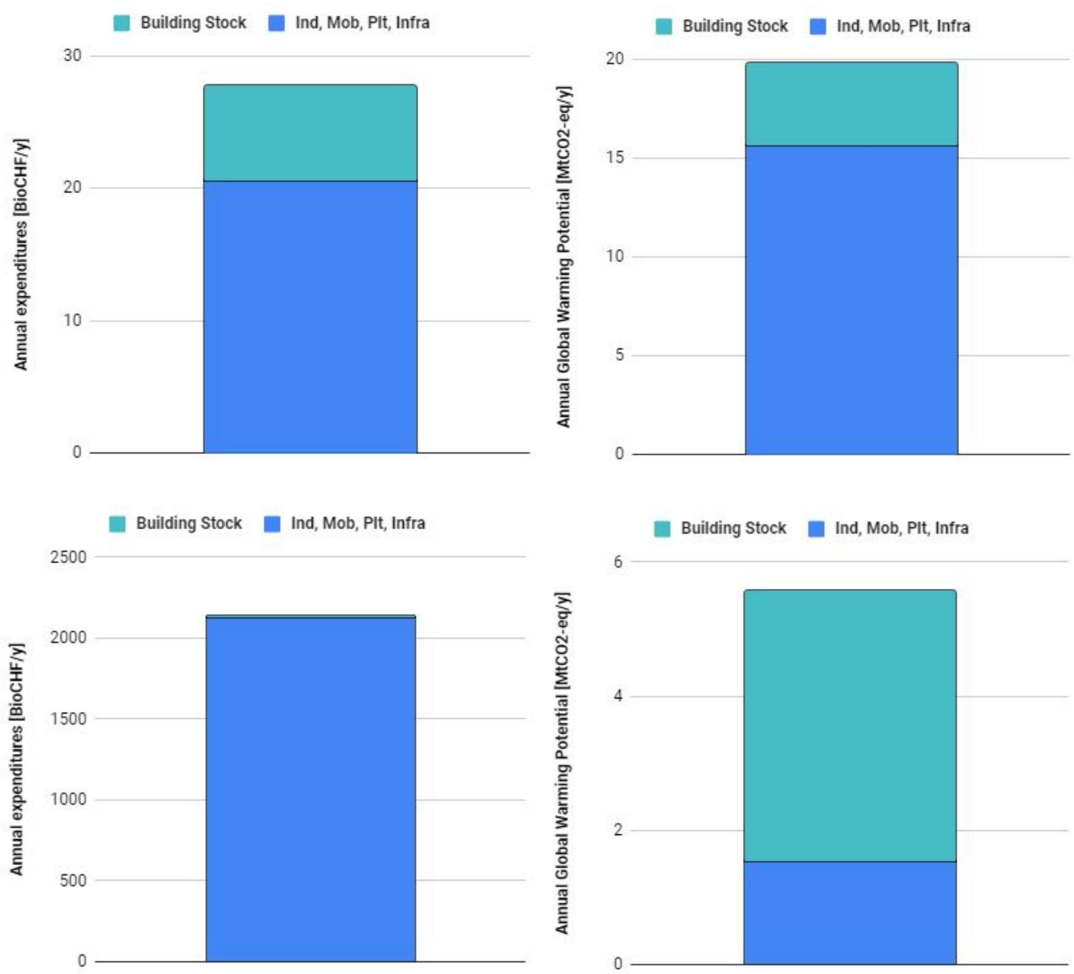


Figure 3.3: Costs (left hand-side) & emissions (right hand-side) of the national energy system under TOTEX (top) and GWP (bottom) optimization

Then, as introduced at the beginning of this section, additional parameters can be extracted for analysis of the building stock optimization by the MILP within a wider environment than in SBD. First, Figure 3.4 displays the scenario options allocation among the 105 typical buildings. It shows that the TOTEX-optimization in ES leads to a combination of the 5 first scenarios from SBD, while the GWP-optimization induces a more spread partition among all the scenario options, except the last one (being the full GWP-optimization in SBD).

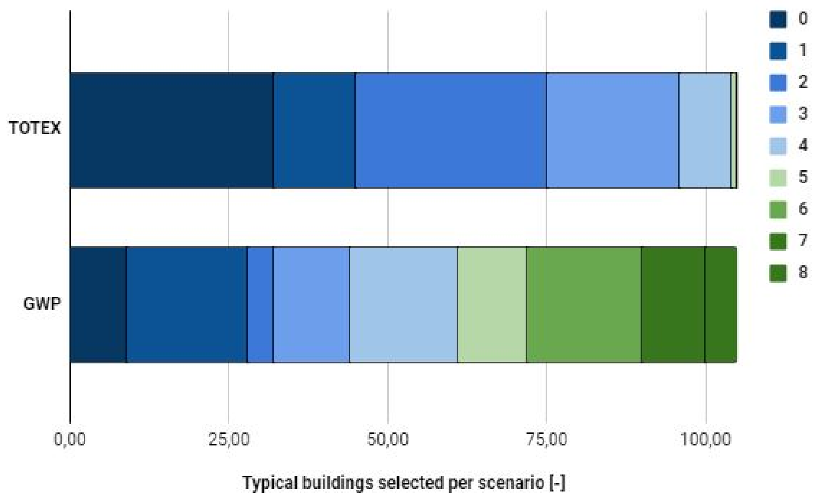


Figure 3.4: Scenario options selection of the building stock under the two objective optimizations

Then, Figure 3.5 shows the resulting installation of the renovation option, both in terms of number of renovated typical buildings (left hand-side) and as a share of building stock ERA renovated. One can read from this the very little use of the renovation option, as it concerns 4.76% of the typical buildings and 2.74% of the national ERA under GWP-optimization, and as it does not even appear in the TOTEX-optimization.

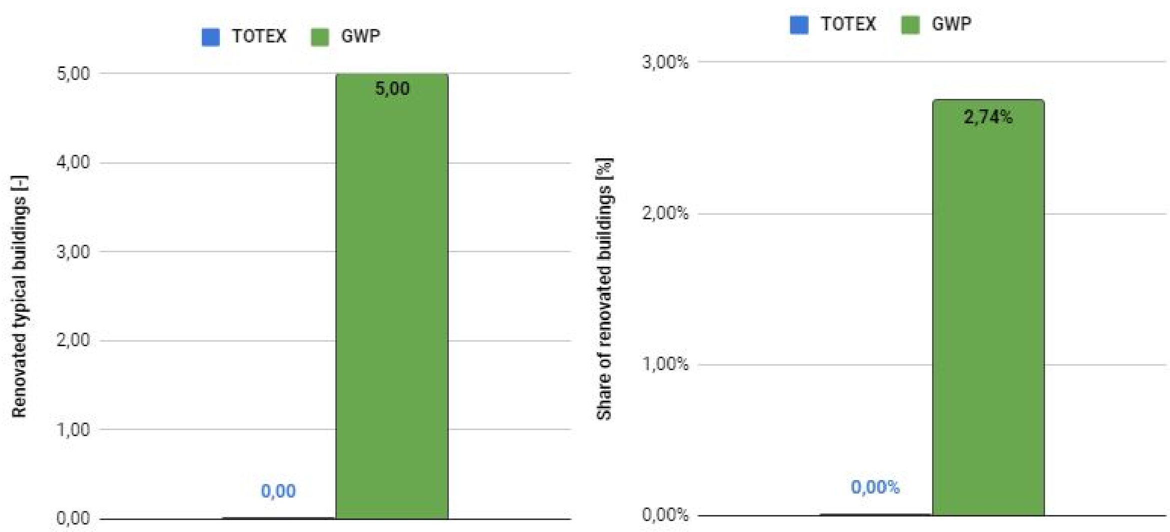


Figure 3.5: Share of renovated buildings under the two objective optimizations

Figure 3.6 displays the energy demand & production of the total building stock as either natural gas (NG) or electricity (of which production, as considered as a supply to the grid and thus a flow leaving the building energy system, is displayed as negative). A comparison between the two objectives shows a reduction of the electricity demand in favor of natural gas demand for the environmentally

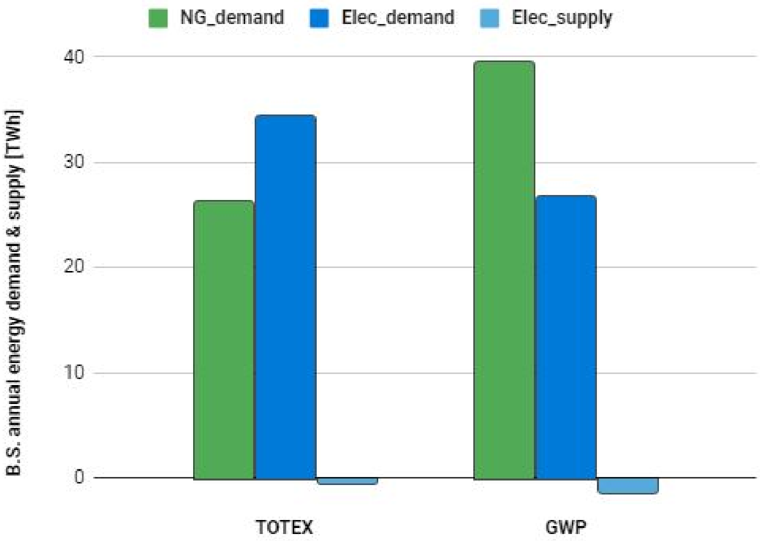


Figure 3.6: Energy demand and supply of the building stock under the two objective optimizations

optimal solution, as well as a slight increase of electricity supply - still low compared to the other resource flows.

Finally, Figure 3.7 displays the total installation of technologies within the buildings. It shows consequent capacities of Electrical Heaters (EH) (respectively 26.71 and 25.79 GW_{th} for the two objectives), followed by natural gas Boiler (BO) (15.35 and 15.82 GW_{th}), and then a combination of renewable energy technologies that are Air-Water Heat Pump (AWHP), PV & Thermal Solar (TS) panels. It shall be noted however that the sizes of the three later technologies are expressed in GW_e, and that it therefore represents the input power (of the compressor) of the AWHP. The output power, depending on external conditions and time-dependent, can thus not be displayed here but is usually 3 to 6 times higher than what is indicated here. Also, it shall be noted that even though EH have a significant installed size, an analysis of SBD results show that they are actually used as a back-up source of energy for extreme periods, and actually not used much throughout the year. In addition, it is important to bear in mind that these technologies will surely be subject to regulation and limitations in the near future. From several SBD runs, it appears that they would be replaced either by natural gas boilers, cogeneration units or Solid Oxyd Fuel Cell (SOFC), depending on the objective, to perform this back-up role.
The variation between the two objectives shows little modifications of the technologies installed size, which is more noticeable for the two solar technologies (PV & TS) and the electric batteries (BA).

Finally, the model allows to dive deeper into the building stock granularity and to generate results per cluster. A more detailed analysis of the relative impact of clusters on the building stock is conducted in section 3.3.1, yet the values of the basic solution are displayed below.
First of all, the same energy demand & supply of resources is shown in Figure 3.8. It illustrates not

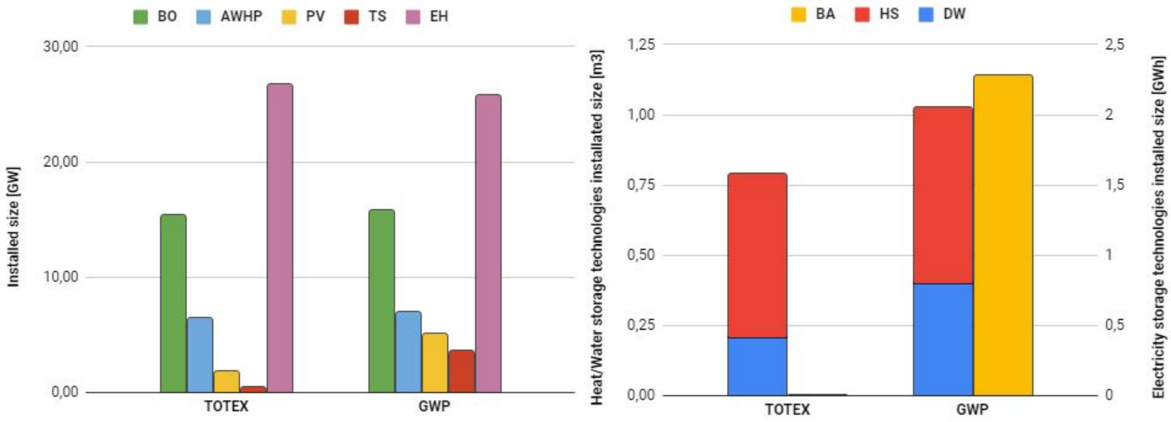


Figure 3.7: Production (left hand-side) & storage (right hand-side) technologies installed sizes of the building stock, under the two objective optimizations

only the disparities in amplitude of demand between the seven clusters but also the relative difference between electricity and natural gas demand for each of them. The first one is induced both by climatic conditions (and resulting energy demand per building) and by the cluster ERA representativeness in the total building stock. The right hand-side of the figure shows that the GWP-optimization induces a increased demand for natural gas (lowering the demand for electricity), except for two clusters ($C1$ & $C5$, respectively characterized by the climatic conditions of Bern & Lugano).

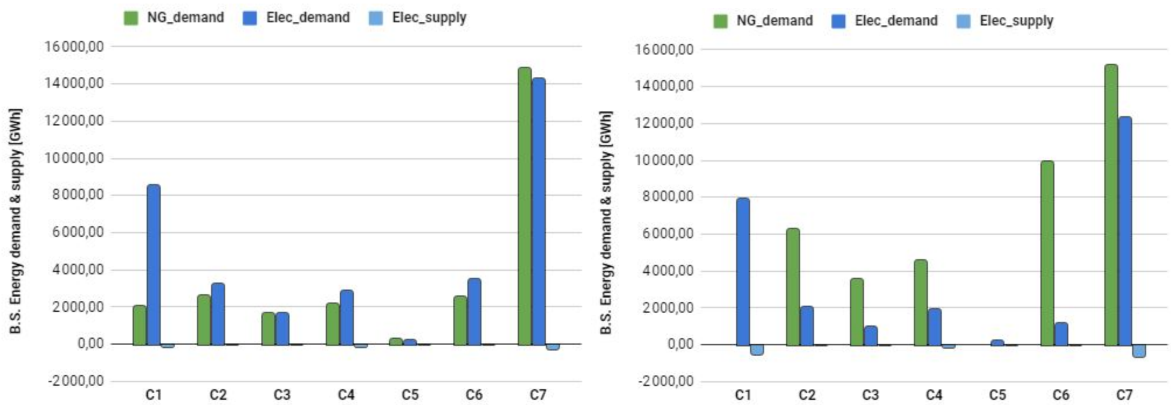


Figure 3.8: Clusters energy demand and supply under TOTEX (left hand-side) and GWP (right hand-side) optimization

Finally, and as for the building stock, Figure 3.9 displays the total technologies installed sizes per cluster. As for the resources graphs in Figure 3.8, it allows to grasp not only the difference in amplitude of capacity between the different clusters, but also their differences in energy mix. It shall be noted as well that the installed size of boilers (BO) evolves similarly to the demand for natural gas between the two objectives (respectively TOTEX on the top and GWP on the bottom of the figure), which is not surprising. In addition, it allows to notice the appearance of TS panels and the increase of PV panels installation, which are more or less significant depending on the clusters. It appears also that the most consequent capacities of EH and Heat Storage (HS) are installed in clusters $C1$ & $C7$ (representing the "Bern-Liebefeld" and "Zuerich-SMA" climatic conditions), which represent respectively 23.3% & 46.6% of the total building stock ERA. One should be aware that, in the storage technologies graphs (on the right hand-side of the figure), the battery (BA) is displayed with respect to the right vertical axis. This is induced by the fact that its installation is measured in GWh, while the installation of HS & Domestic Water tank (DW) is measured in m^3. But more importantly, it highlights how little its capacity is under TOTEX-optimization.

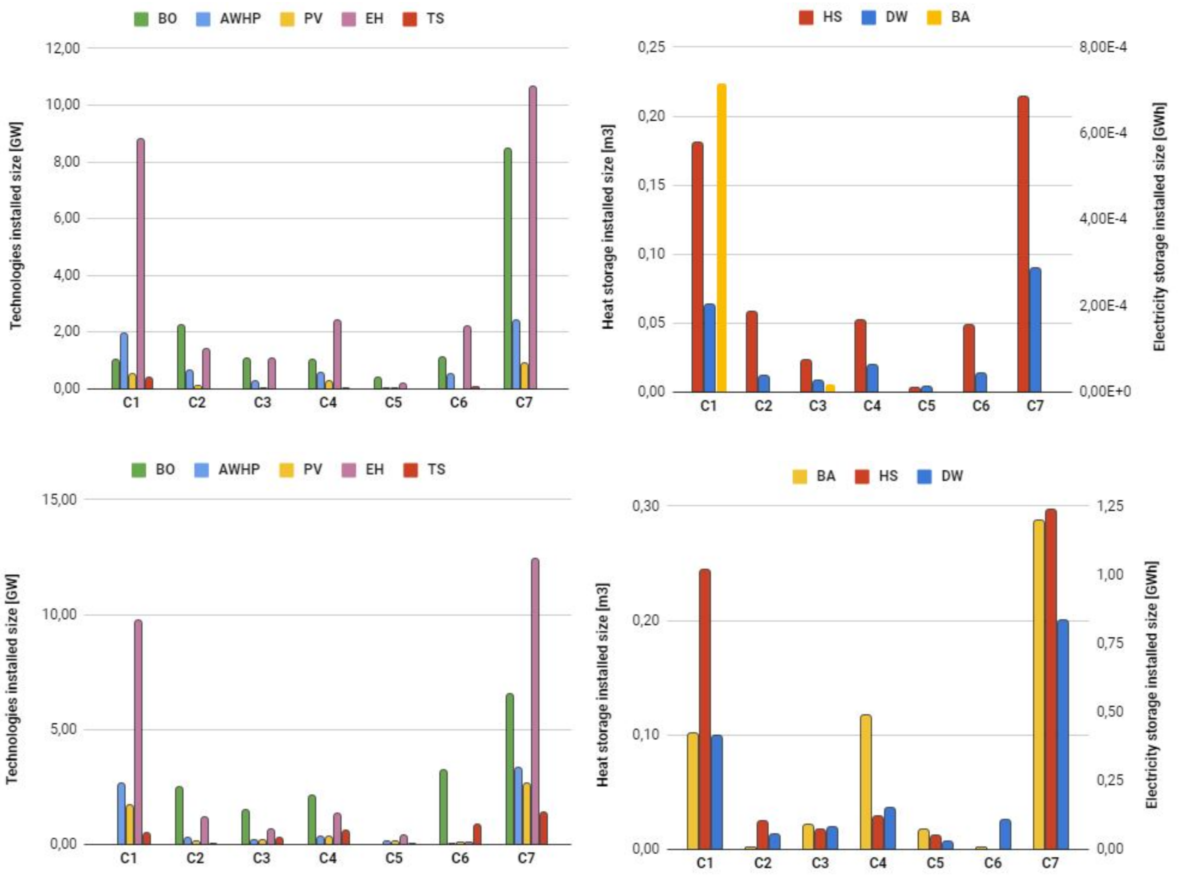


Figure 3.9: Clusters installed capacity of production (left hand-side) and storage (right hand-side) technologies, under TOTEX (top) and GWP (bottom) optimization

3.1.3 Comparison with no building stock optimization

In this section, the results of the developed model are compared with the original ES model (for the Swiss 2050 case study), in order to better grasp the impact of the separate optimization of the building stock on the global energy system.

Similarly as in Section 3.1.2, Figure 3.10 displays the national energy system total cost (left hand-side) and total emissions (right hand-side) under TOTEX (top) and GWP (bottom) optimization. It shows that the global system is always more expensive and carbon intensive with separate building stock optimization. The difference is relatively very small for carbon emissions under TOTEX-optimization and for total expenditures under GWP-optimization, but it is very significant for the objective functions of the optimization (i.e. TOTEX & GWP under their own minimization).

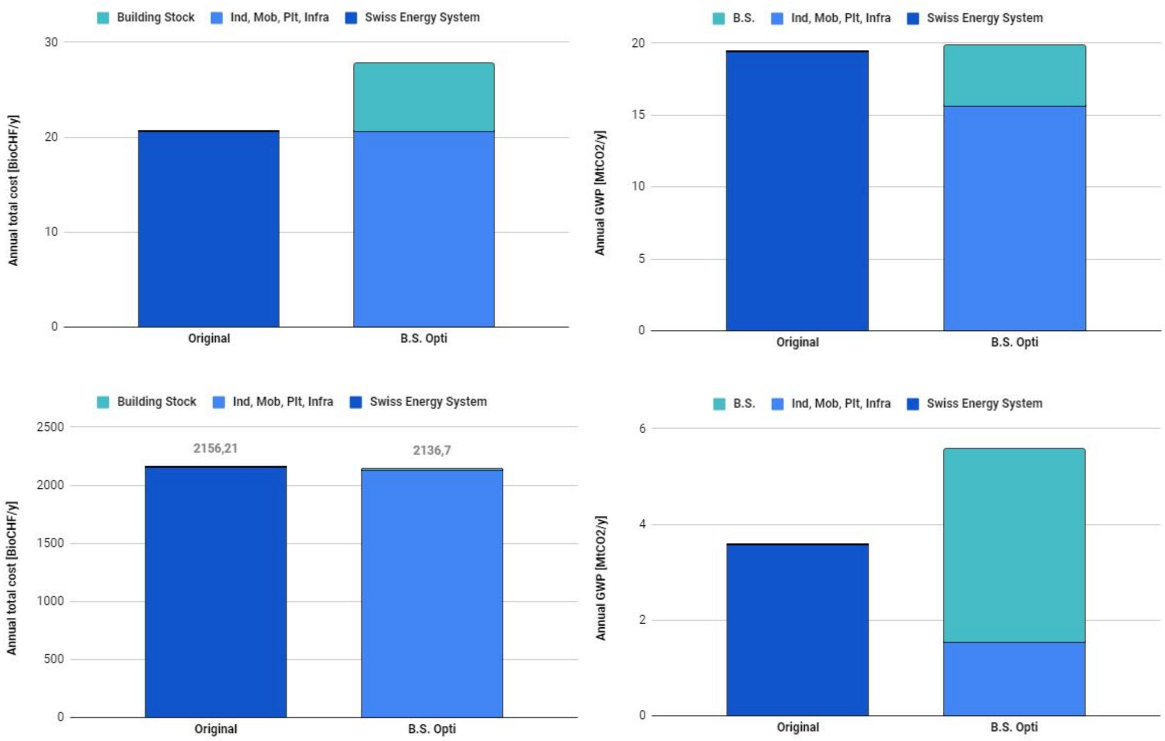


Figure 3.10: Costs (left hand-side) & emissions (right hand-side) of the national energy system under TOTEX (top) and GWP (bottom) optimization, with and without separate building stock optimization

In the meantime, Figure 3.11, displaying the variation of total cost and total emissions between TOTEX & GWP optimizations, shows that it is less significant with separate optimization of the building stock. This means that the two "optimal" solutions are closer in the current model, which could either be induced by efficient use of resources, or by lower flexibility of the model.

Figure 3.11: Total cost and emissions variations between TOTEX and GWP optimizations, with and without separate building stock optimization

Finally, and most importantly, the concrete and physical disparities between the two models are displayed in Figure 3.12, which illustrates the installed capacities of the most relevant technologies gathered in 4 categories: power plants, decentralized (i.e. local production of energy, either in buildings, factories, services, etc.), District Heat Network (DHN) (local grid system providing heat to several buildings and facilities) and SBD technologies (the ones from SBD optimization, specific to the building stock). The figure shows that, with the separate building stock optimization and under TOTEX-optimization, there is a significant decrease of decentralized technologies, as well as a tendency to lower the capacity of the DHN. The total capacity of the power plants is however increased, and the total installed size of building-specific (SBD) technologies is very consequent compared to the rest. It shall be noted as well that, even if it is not displayed here, the capacity of the technologies local to the industry sector is relatively significantly reduced in the current model, while the national resource consumption increases. On the other hand, the GWP-optimization presents the same trends and evolutions with the implementation of separate building stock optimization. However, the installed sizes of both decentralized technologies and DHN are so impressively high that it is almost imperceptible. Yet the capacity of power plants still increases by 53.3%, the one of industry-specific technologies decreases by 53.5%, and the national resource consumption increases by 20.1%.

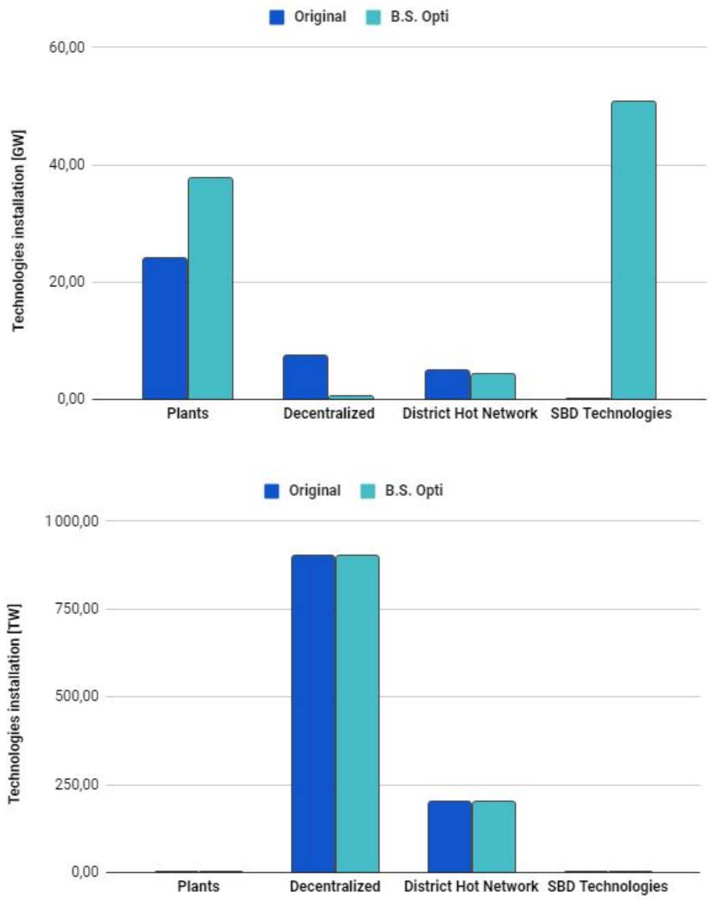


Figure 3.12: National technologies installation, under TOTEX (top) and GWP (bottom) optimization, with and without separate B.S. optimization

3.1.4 Scaling error mitigation

When analysing the results per cluster (regarding section 3.3.1) it appeared that the Cluster 2, corresponding to the Davos climatic conditions, was the most impactful one. Even though it has the most intense climatic conditions and thus the biggest energy demand per square meter, it was very surprising as it was not expected to be the largest one (in terms of ERA representativeness in Switzerland).

However, it appears that the scaling factors extracted from PSD and used to scale up the results from SBD were actually defined in a wrong order. Indeed, the clusters are listed by alphabetical order in both the python code for SBD implementation and in PSD literature, but that is not the case of the 105 typical buildings characterization in the other files provided by Paul Stadler's study. Therefore, the buildings were optimized correctly in SBD (as considered separately), yet their scaling up did not correspond to their climatic conditions, and thus the cluster representativeness as well as the total building stock parameters values were overestimated.

The impact of this scaling mismatch is studied hereby. Note that this error was corrected for sections 3.1.2, 3.1.3 and 3.3.1, but not for the later comparison on Global Warming, SBD costs and scenario options, as it is supposed to only slightly impact the raw values and not the overall behavior of the system.

Figures 3.13 & 3.14 display the variation in total cost and total emissions respectively of the building stock and the national energy system between the first optimization and the corrected one. They show that the correction slightly reduces the total expenditures and carbon emissions of the building stock, as well as their share with regard to the ones of the national energy system. It also appears that the relative share of operational parameters is also slightly reduced with regard to the construction/investment ones.

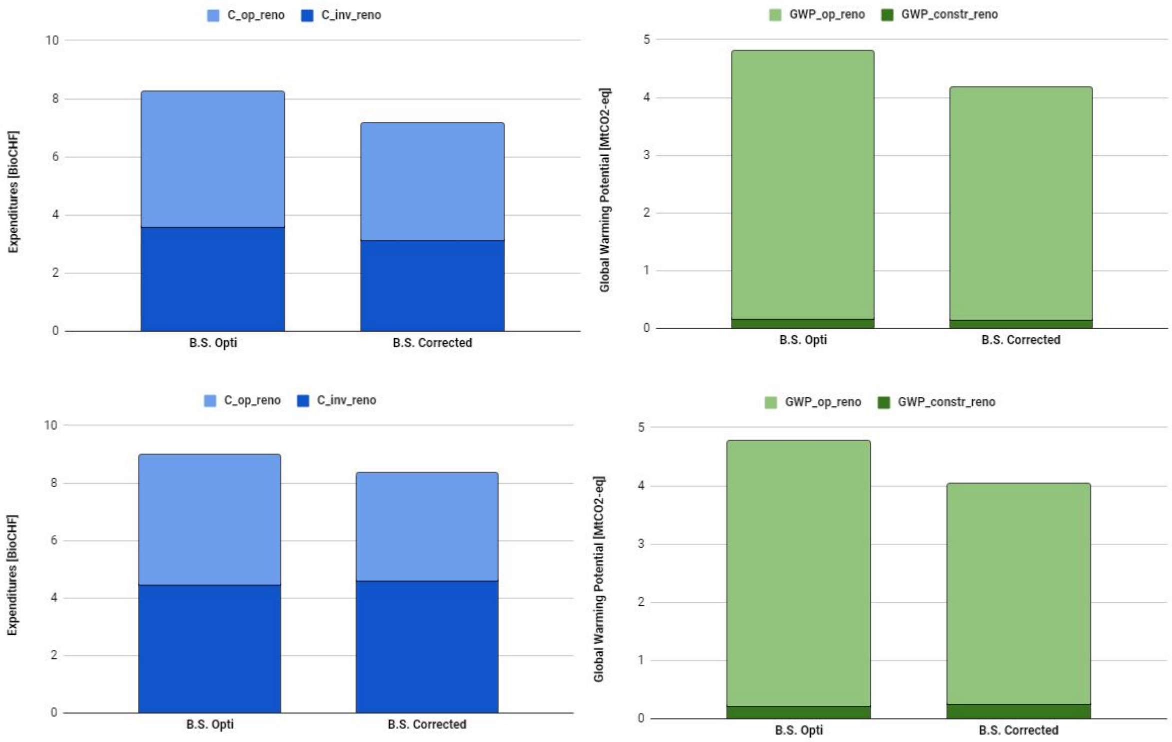


Figure 3.13: Costs (left hand-side) & emissions (right hand-side) of the building stock under TOTEX (top) and GWP (bottom) optimization, with and without corrected scales

Figure 3.15 displays the variations in scenario selection with the correction, which is null under TOTEX-optimization but more noticeable under GWP-optimization, with for example a slight increase of scenario 2 and the disappearance of scenario 9. Below, Figure 3.16 displays the differences in renovation installation, which was already very low before the correction.

Additional figures (Figures B.1-B.3) displaying the resources demand & supply as well as the technologies installed sizes of the building stock are available as well in Section B.1.2. They all highlight the small yet noticeable variations between the first and the corrected building stocks, with modifications of the relative share of each technology and resource, yet not the global energy mix. Because of

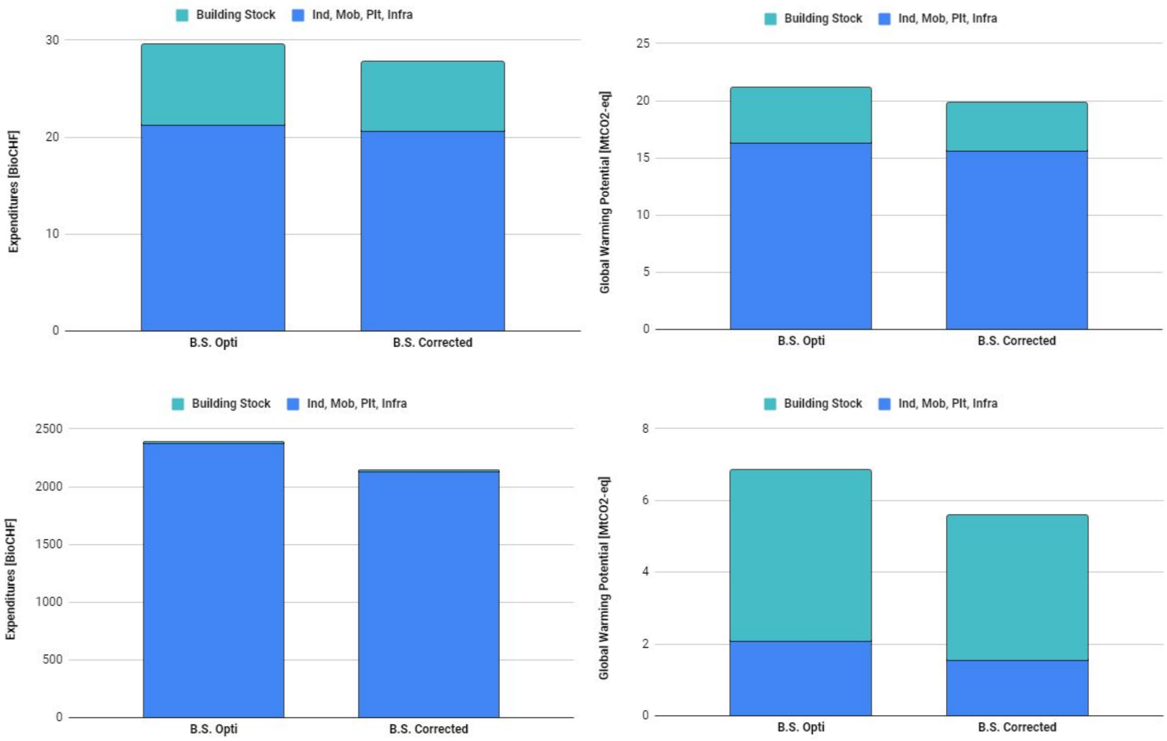


Figure 3.14: Costs (left hand-side) & emissions (right hand-side) of the national energy system under TOTEX (top) and GWP (bottom) optimization, with and without corrected scales

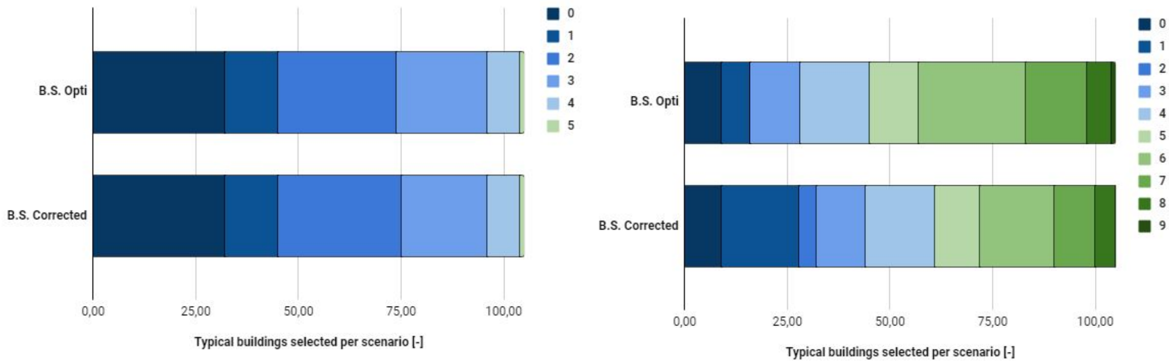


Figure 3.15: Scenario options selection of the building stock, under TOTEX (left hand-side) and GWP (right hand-side) optimization, with and without corrected scales

their redundancy and their importance in the argumentation on the validity of the results presented in the following sections, these figures are displayed in Annex. This is also the case for Figures B.4 & B.5, which describe the relative variation between the first and the corrected optimizations of the resources demand & supply and of the technologies installation. The graphs actually illustrate the change in scaling factors, inducing each cluster to adapt to the new corrected ones. For example, clusters C2 & C3, that were significantly over-estimated, see their total technologies installation and resources demand & supply decrease in order to reach their actual values. This is the opposite for

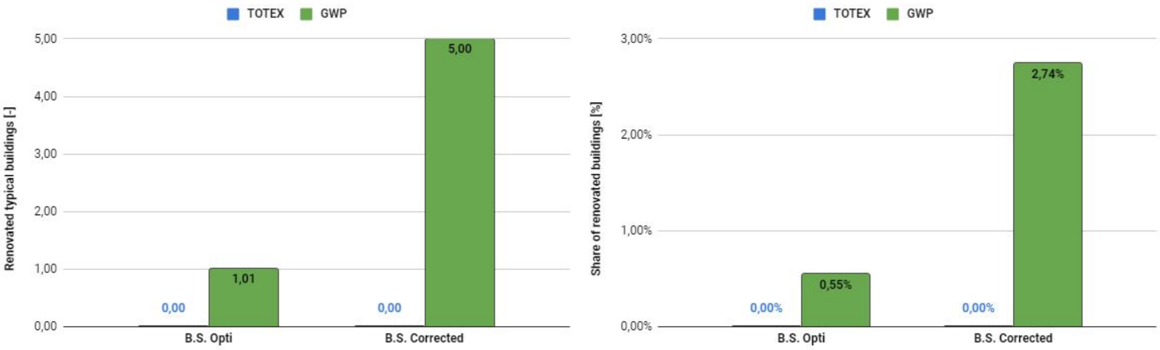


Figure 3.16: Share of renovated buildings, with and without corrected scales

clusters C1 & C3, the two largest ones in terms of ERA, of which parameters are consequently increased. The details on clusters parameters are further described in the dedicated Section 3.3.1.

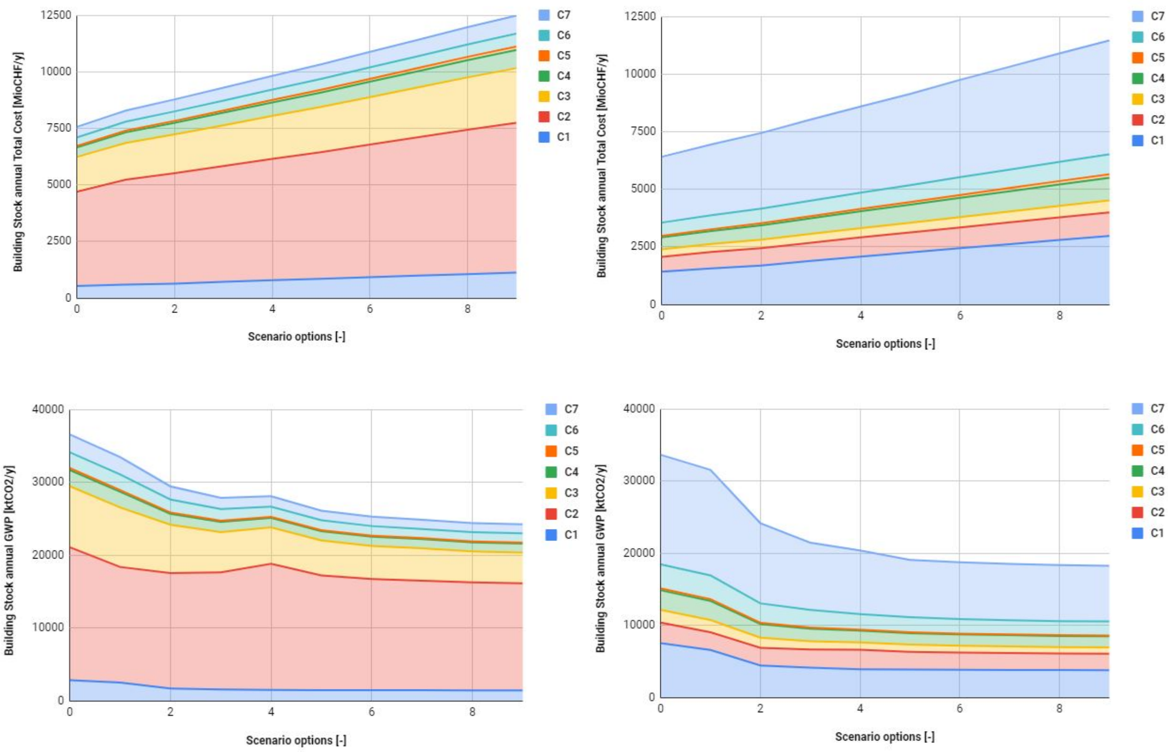


Figure 3.17: Cumulative clusters costs (top) and emissions (bottom), with original (left hand-side) and corrected scaling factors (right hand-side)

Finally, and similarly to what is analyzed in Section 3.3.1, the cumulated total cost and emissions of the seven clusters, per scenario option, are displayed in Figure 3.17 for the two optimizations. It shows how the impact of the error is significant on clusters individually, while being almost negligible on the total building stock. The normalized total cost and emissions, that are displayed in Section

3.3.1 for the results with the actuated scaling factors, obviously appear to be almost identical in both cases, as they are normalized per m^2 based on their ERA, which is the parameter on which the error is based.

3.2 Impact of renovation

3.2.1 Approach

Now that the general results of the model have been generated, and that the first project question, about the building stock impact on the national energy system, has been addressed, the impact of renovation will now be studied. Indeed, this option proposed by Paul Stadler in PSD is of particular interest in the context.

To do so, the whole process performed with SBD (steps 2 & 3 of the project structure) will be executed twice. In a first time with forced installation of renovation for each eligible building, and in a second time with completely ignoring the renovation option. This is done by adding to the SBD AMPL model a new constraint on the use and installation of the technology. By doing this, two sets of input *.dat* files are created for EnergyScope, with either 0% or 100% installation of renovation option. Therefore, an additional constraint can be added to the ES model to impose a percentage of installation of the renovation.

All parameters defined from SBD output and added to the ES model (Section 2.5) are being doubled as imported twice, each time remained with an additional subscript, either *_on* or *_off* whether renovation is forced or excluded.

In addition, a *scale.dat* file is added to be able to judge on the real share of implemented renovations, not in terms of iterations/building types but rather in terms of ERA.

Then, the constraints and parameters remain the same, except that the use of the above mentioned parameters are now put in conflict (apply either the scenario with or without renovation, as if the scenarios were doubled and only one of the 10 first or one of the 10 last could be used) and that the total share of renovation is constrained.

```
param reno_share >=0 default 0.25;
param scale {b in BUILDINGS} >=0 default 1000;
param Scale := sum{b in BUILDINGS} scale[b];

subject to f_s_ID_constraint{b in BUILDINGS}:
    sum {s in SCENARIOS} (f_s_ID_on[b,s] + f_s_ID_off[b,s]) = 1;

subject to reno_share_constraint:
    sum {b in BUILDINGS, s in SCENARIOS} ((f_s_ID_on[b,s] +
        f_s_ID_off[b,s])*scale[b]) = reno_share * Scale;
```

3.2.2 Results

The results of these optimizations are gathered in Table B.2, and are actually reduced to the two extreme scenarios of 100% and 0% of renovation. Indeed, it appears that the current modelling of refurbishment, even if applied to the whole building stock, has almost no impact on the system. Similarly to the general results, Figures 3.18 & 3.19 display the resulting costs and emissions of the building stock as well as its representativeness in the national energy system. They show how minor the variations are, and it shall be noted that most of them are not perceptible with the used scales. The rest of the results are displayed in Figures (B.6-B.10) in Section B.1.3 of the Annex, as the differences are imperceptible.

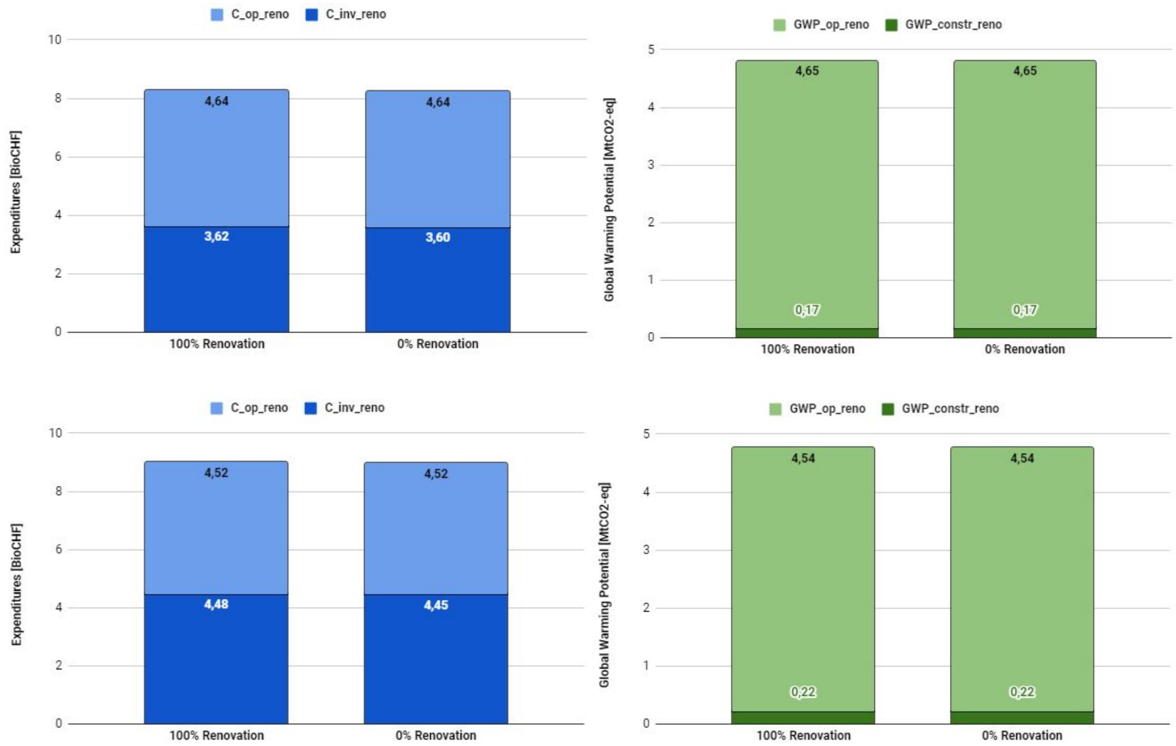


Figure 3.18: Costs (left hand-side) & emissions (right hand-side) of the building stock under TOTEX (top) and GWP (bottom) optimization, with forced and avoided renovation installation

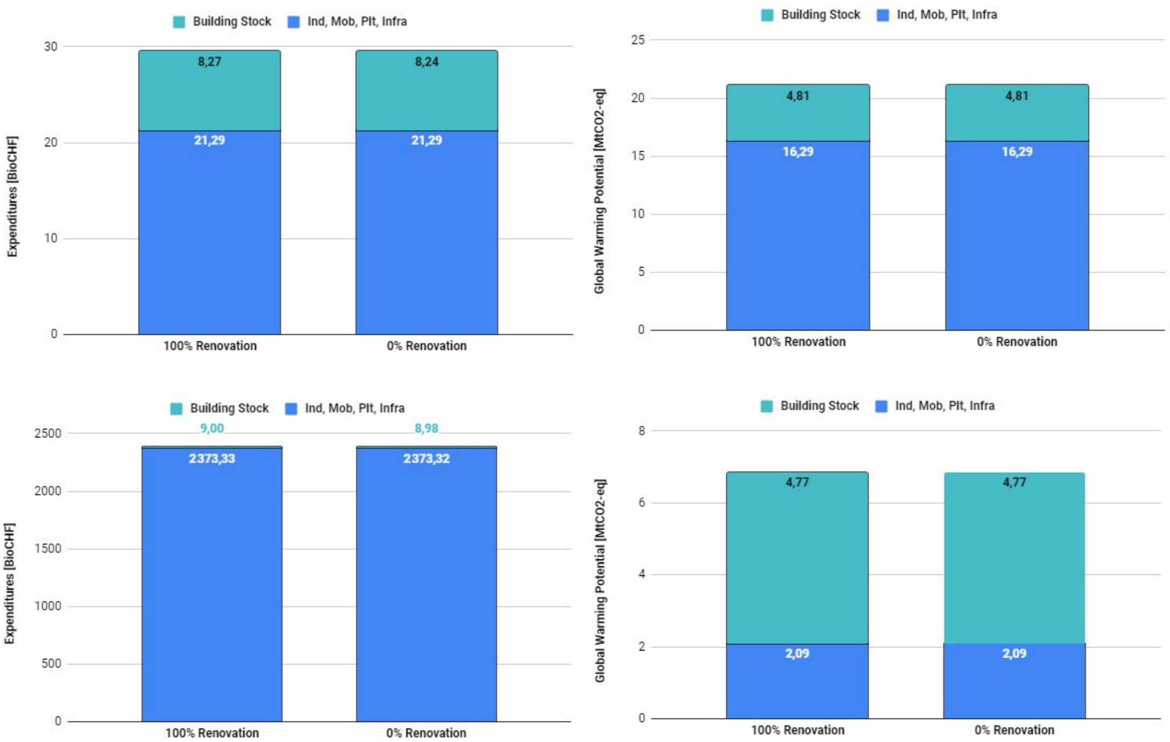


Figure 3.19: Costs (left hand-side) & emissions (right hand-side) of the national energy system under TOTEX (top) and GWP (bottom) optimization, with forced and avoided renovation installation

3.3 Impact of Climatic Conditions

The third sub-question of this work addressed the impact of climatic conditions on building stock and global energy system optimization. The geographical clustering of the Swiss building stock already brings some granularity on weather disparities and allows to perform a first analysis on the SBD output results and the differences between the seven clusters. This is conducted hereafter in Section 3.3.1. Meanwhile, the automation of this study and the adaptability to different geographical clustering and countries have the ambition to allow for a comparison of final results under several climatic conditions, in order to really assess their impact. Therefore, a first analysis is conducted, on the potential impact of global warming on building stock and national energy optimization (Section 3.3.2).

3.3.1 Impact of geographical clusters

In this section, the results from SBD are directly analyzed in order to better grasp the characteristics of each cluster and the disparities between them. Their main parameters are summarized in Table 3.1 for clarity purposes and in order to perform normalization based on their total ERA, which may allow to focus on their specific climatic conditions rather than only on their representativeness or weight in the geographical clustering.

Table 3.1: Clusters main parameters

	Name/Weather Station	ERA [mio m^2]	ERA Share [%]	T_{amb} [°C]	GHI [kWh/m^2]
C1	Bern-Liebefeld	155.95	23.29%	9.48	136.25
C2	Davos	48.16	7.19%	4.38	163.16
C3	Disentis	32.86	4.91%	7.04	153.01
C4	Geneve-Cointrin	58.98	8.81%	11.03	142.05
C5	Lugano	11.25	1.68%	12.76	144.03
C6	Piotta	50.16	7.49%	8.11	139.37
C7	Zürich-SMA	312.19	46.63%	9.87	127.85

Figure 3.20 illustrates the cumulated total cost and total emissions of the seven clusters for the 10 scenario options, both as raw and normalized values. It shows how clusters C1 & C7 (Bern & Zürich, the largest ones in terms of ERA) represent the biggest economic and environmental impact in the national building stock, while clusters C2 & C6 (Davos & Piotta, the ones with the most extreme conditions) are actually slightly more significant when considering the normalized values.

For clearer comparison, a TOTEX-GWP pareto fronts comparison is performed between the 7 clusters, once with raw values (Figure 3.21) and once with normalized values (Figure 3.22). The graphs highlight the same comparison between the clusters $C1$ & $C7$ and $C2$ & $C6$. In addition, it appears that cluster $C5$ (Lugano), is actually the less impacting one in both cases, which relates to the fact that it is the least represented one (1.68% of the total ERA), with somehow the best climatic conditions (highest average temperature and third highest GHI).
Additional figures on the resources consumption and production per cluster are displayed in annex (Figures X-Y, Section B.1.4) and illustrates similar disparities between the clusters as well as the global trend on preferences for either natural gas or electricity reliance depending on the scenarios. It also displays the renovation installation per cluster and per scenario option (Figure Z), as well as their self-consumption and self-sufficiency parameters (Figure A).

It shall be noted that the shape of Pareto front of cluster $C2$, presented above, is quite surprising. Indeed, as it is supposed to be a progressive evolution from one objective to the other, with no change in direction. One could assume that it may be partly explained by the used method of optimizing only one objective and forcing the other one (because of the constraints linked to the iterative optimizations in *Loop.py*). However, the following results are displayed in order to understand the behavior of the cluster buildings and energy mix in SBD, as the deviation is really significant.
Figure 3.23 illustrates in more details the total costs as well as the carbon emissions of the cluster

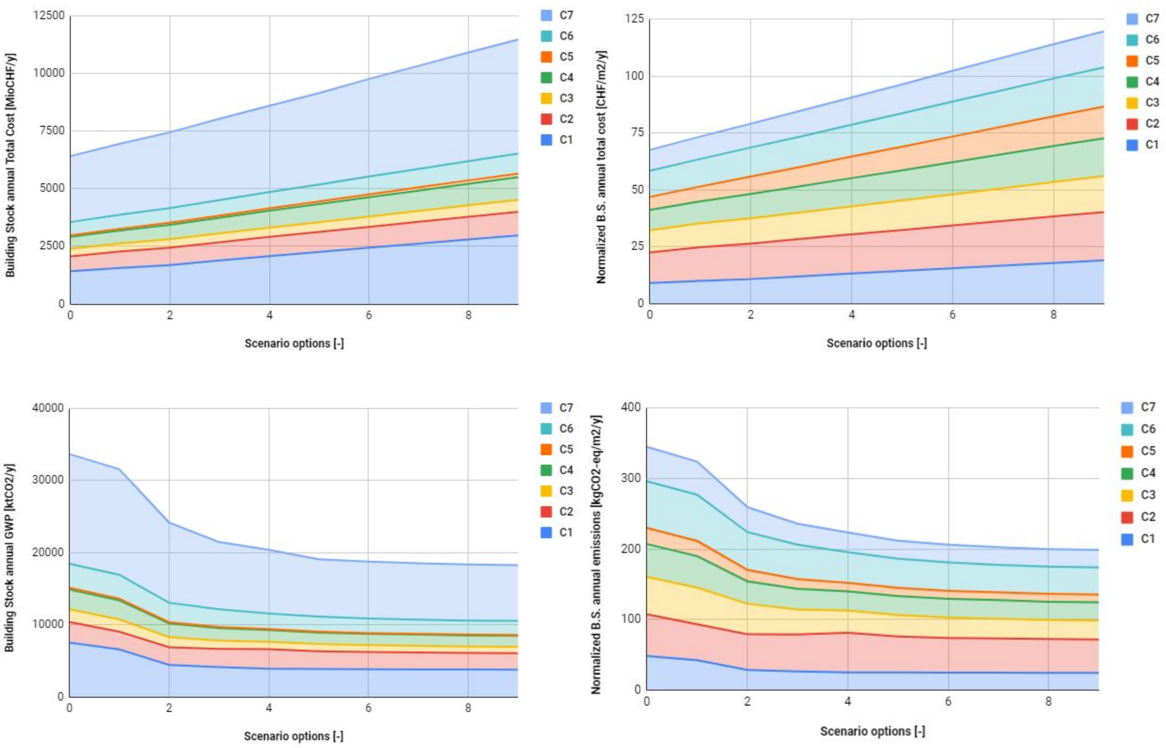


Figure 3.20: Cumulative clusters costs (top) and emissions (bottom), as total (left hand-side) or normalized values (right-hand side)

C2 (Davos) under the several scenario options. It shows that while the total cost linearly increases (because of the constraint imposed for the Pareto front design), the GWP progressively decreases, as expected, except for scenarios 3 & 4, for which it actually consequently increases. The second graph shows that this increase is induced by the operational emissions rather than by the construction ones. Therefore, this behavior cannot be explained (only) by the installation of new technologies, especially not of PV or TS panels that present no operational emissions, neither of SOFC nor Air-Air Heat Pump (AAHP) that are not installed at all (which is almost the case of BA at this point).

Figure 3.24 (focusing on the two technologies of which installation changes the most under the considered scenarios) however illustrates a variation that may help explaining this behavior. Indeed, between scenarios 2 and 3, the EH capacity overpasses the one of BO, and the difference consequently widens in scenario 4. It may be explained by the fact that, in SBD, the system tends to rely on electricity (even though it is more carbon intensive with ES parameters values than natural gas) with GWP objective. Indeed, it allows for clean & local energy production from solar energy, as well as to rely on heat pumps, that are very efficient technologies in terms of resource consumption. Therefore, the optimizer progressively tends to replace the NG-relying technologies by electricity-relying ones. Yet, in scenario 3 & 4, PV panels and batteries are not yet significantly deployed, neither are the heat pumps, and the need for back-up technologies enforces the installation of electrical heaters, which are not efficient and thus increases the carbon emissions due to operations.

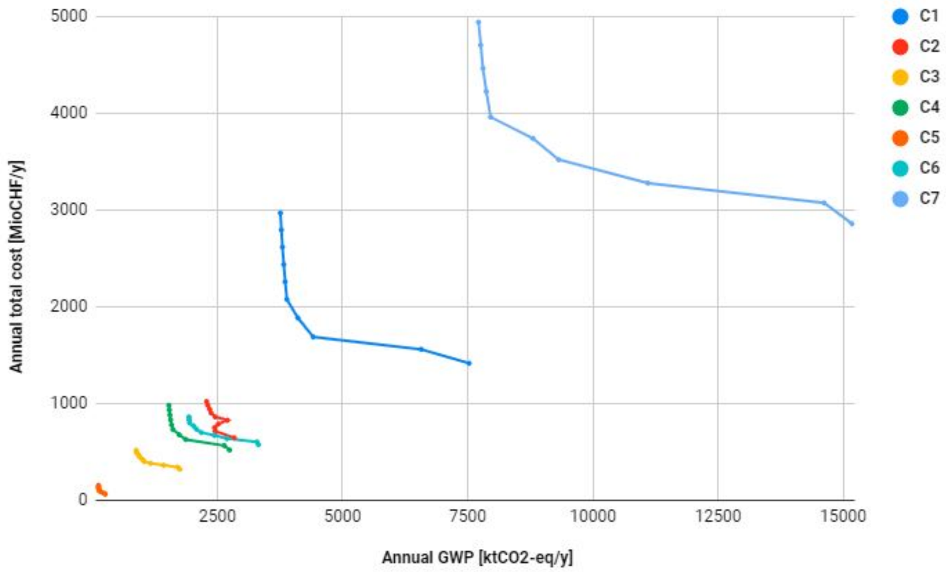


Figure 3.21: Clusters TOTEX-GWP Pareto fronts

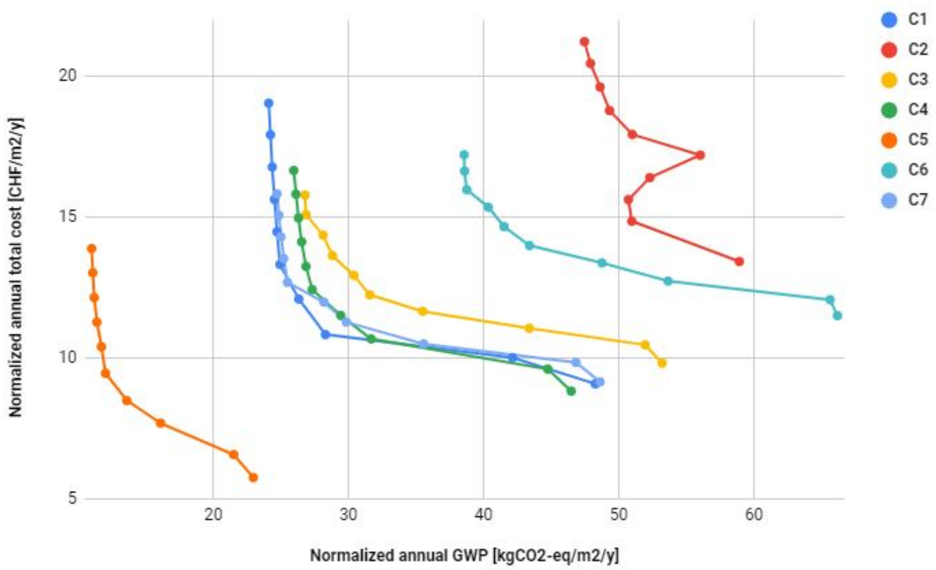


Figure 3.22: Clusters normalized TOTEX-GWP Pareto fronts

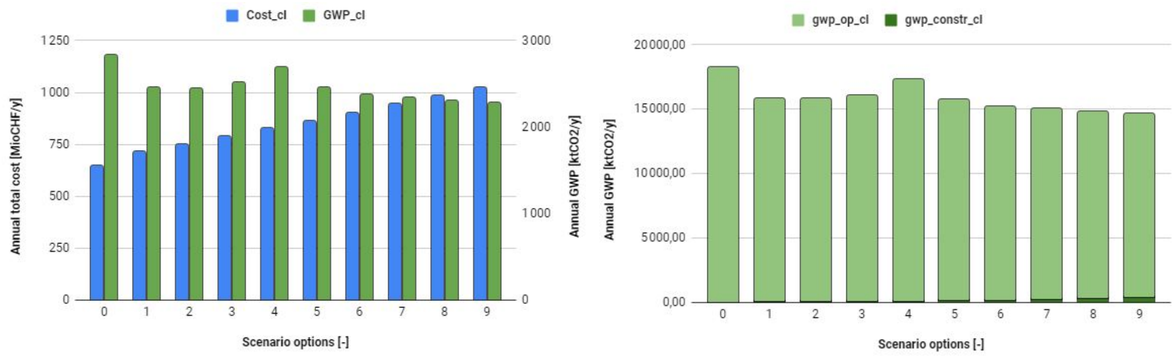


Figure 3.23: Cluster $C2$ total cost and emissions (left hand-side), operational and construction emissions (right hand-side) evolution with the 10 scenario options

3.3.2 Impact of Global Warming

Approach & Motivation

In light of the European Environment Agency statement saying that *"without drastic cuts in global greenhouse gas emissions, even the 2°C limit will already be exceeded before 2050"*, the whole SBD+ES process is performed with an increase of 2°C of the external temperature for all clustered regions. This increase is simply imposed when writing the weather *.dat* files (as input for SBD) from meteorological data, and could be directly proposed as an input parameter in the *Typical Building.py* interface.

Note that this approach is an inexact approximation of a "global warming" scenario analyzing as the current version of SBD does not include air-conditioning. Indeed, the increase of the external temperature will therefore rather impact the efficiency of technologies relying on external resources (s.a. PV panels, TV panels, Heat Pumps) and reduce the heating demand, along with the global costs and emissions. However, it is still a valid study of the impact of climatic conditions variations on the building stock, and leaves room for later improvement for a specific study on climate change.

Results

The resulting costs and emissions of the building stock are gathered in Figure 3.25, which shows that they all slightly decreases with the temperature increase, and that it mainly concerns the operational parameters. It can be seen as well in Figure 3.26, displaying the same parameters for the national energy system, where one can notice that the decrease is more significant on the building stock, yet that the rest of the system is impacted as well.

The scenario partition displayed in Figure 3.27 shows that with the variation of ambient temperature, the MILP tends to slightly increase the selection of scenarios close to the GWP-optimization (as well as the one of scenario 2), for both objectives. In the meantime, Figure 3.28 illustrates an increasing interest for renovation under the current conditions.

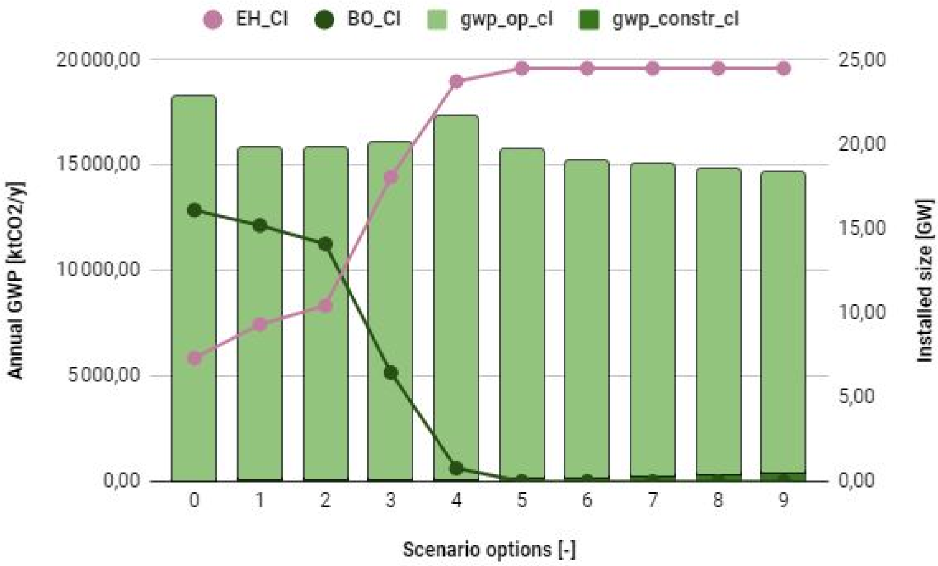


Figure 3.24: Cluster $C2$ operational & construction emissions, Electrical Heaters (EH) and natural gas Boiler (BO) installed capacities evolution with the 10 scenario options

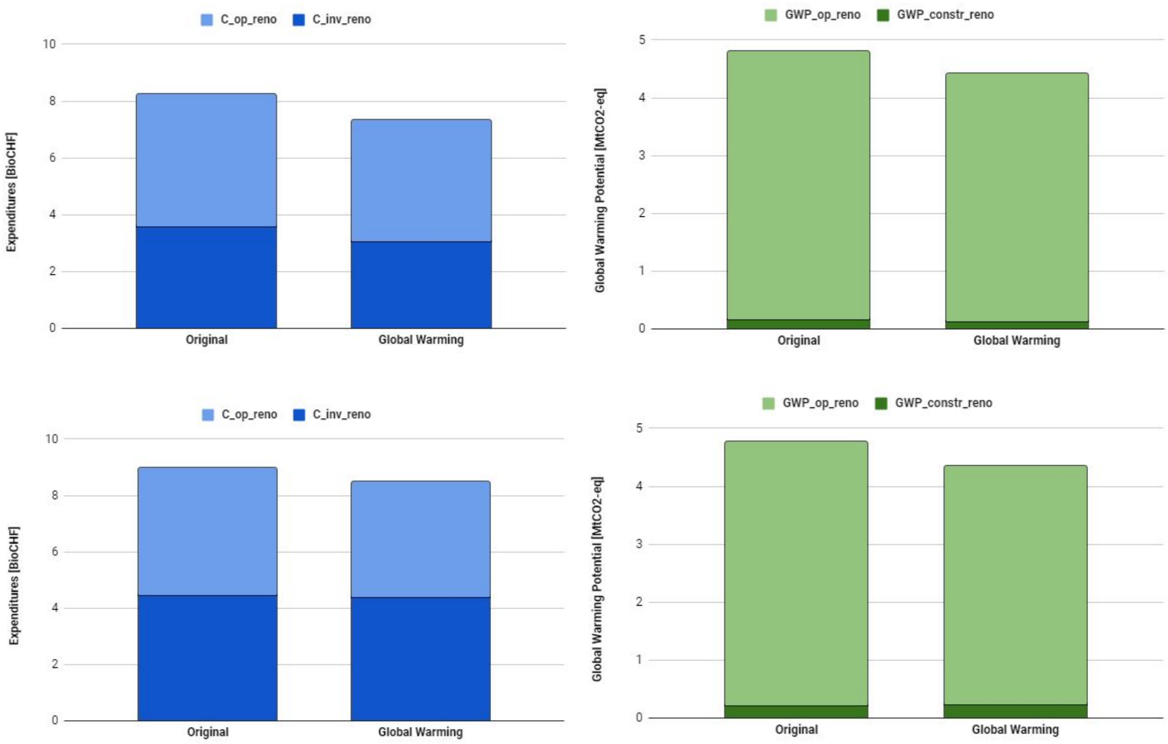


Figure 3.25: Costs (left hand-side) & emissions (right hand-side) of the building stock under TOTEX (top) and GWP (bottom) optimization, with and without consideration of Global Warming

Regarding the resources consumption & production, Figure 3.29 illustrates a global reduction of the energy demand and supply of the building stock, at the exception of a noticeable increase of NG

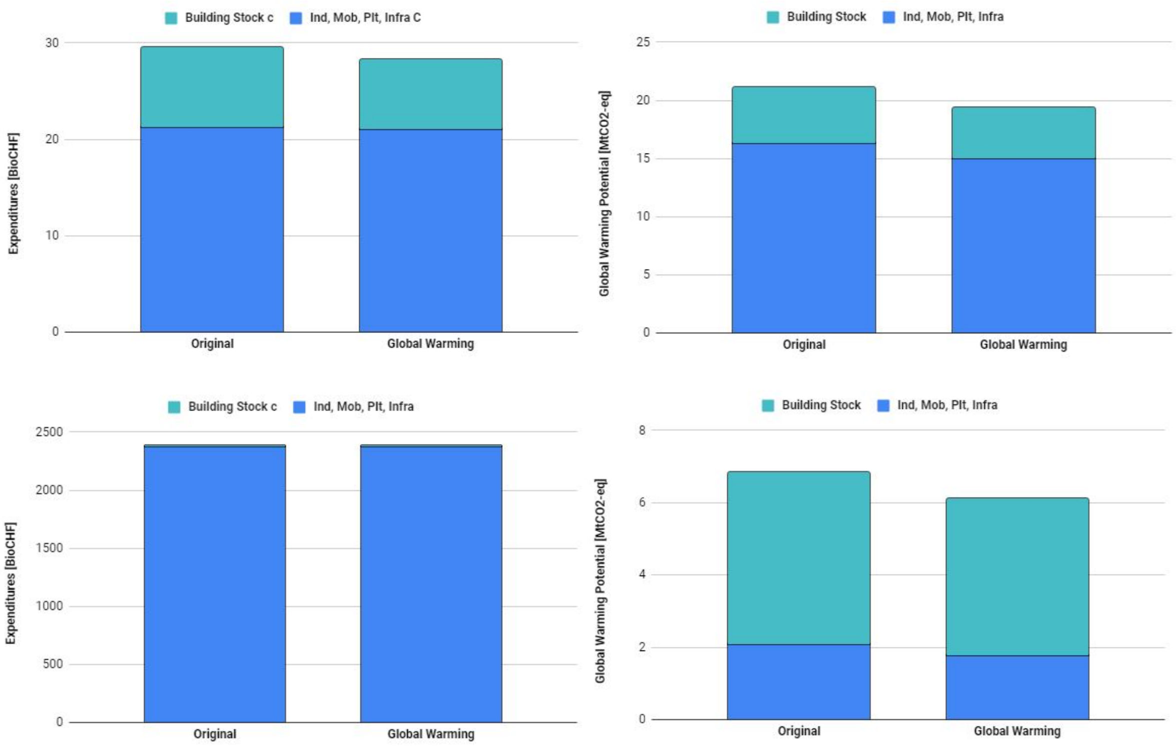


Figure 3.26: Costs (left hand-side) & emissions (right hand-side) of the national energy system under TOTEX (top) and GWP (bottom) optimization, with and without Global Warming consideration

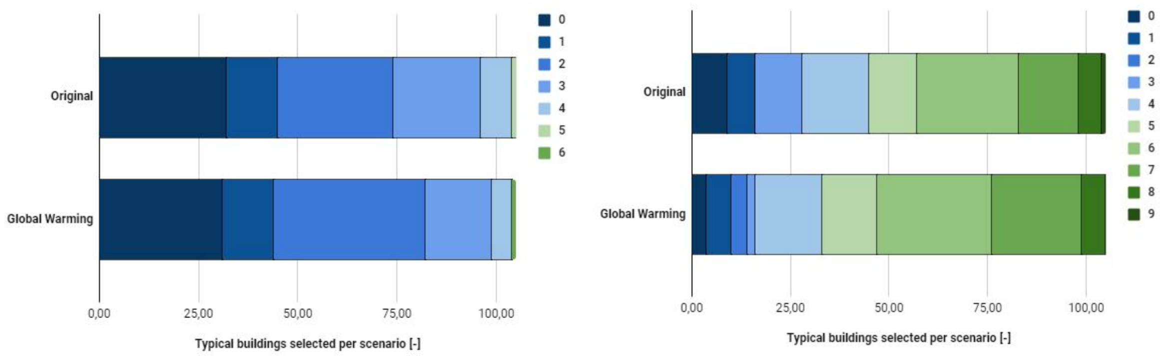


Figure 3.27: Scenario options selection of the building stock, under TOTEX (left hand-side) and GWP (right hand-side) optimization, with and without Global Warming consideration

demand under TOTEX-optimization. In parallel, the installed sizes of AWHP, PV panels and even natural gas boiler (BO) are reduced, while the ones of TS panels and electrical heaters (EH) are being increased, more or less significantly depending on the objective function. It shall be noted that it is also the case for storage technologies, including HS under GWP-optimization. These results are illustrated in Figure 3.30 & 3.31.

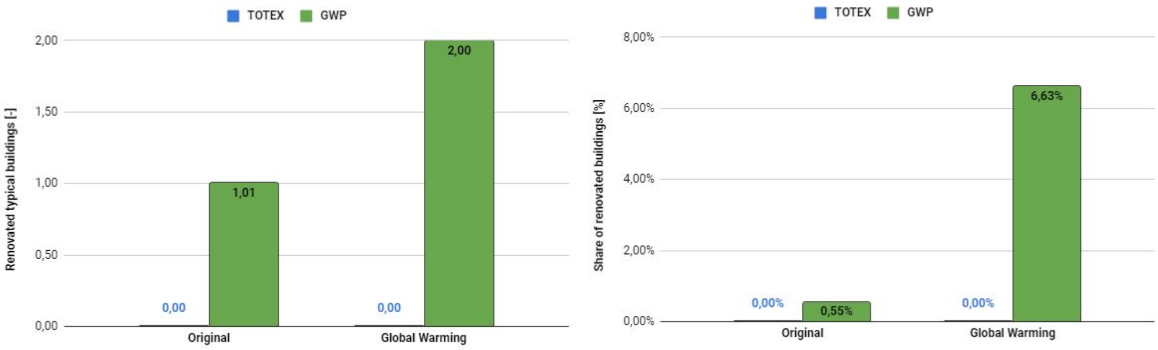


Figure 3.28: Share of renovated buildings, with and without Global Warming consideration

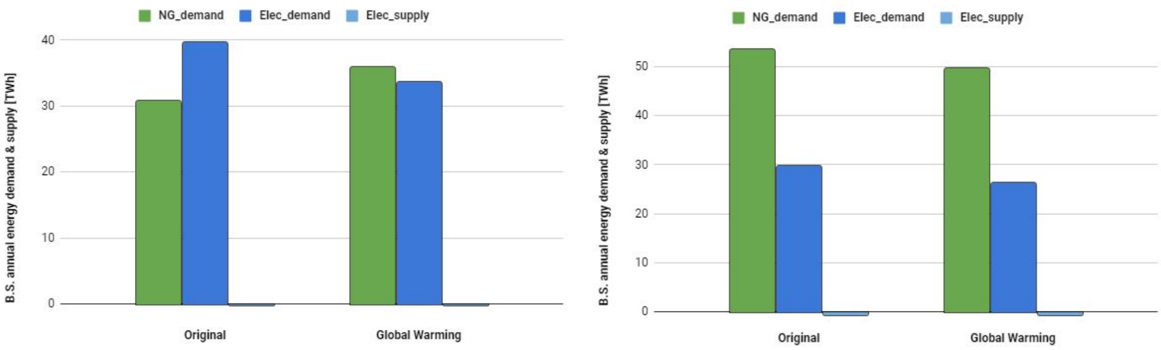


Figure 3.29: Energy demand and supply of the building stock under TOTEX (left hand-side) and GWP (right hand-side) optimization, with and without consideration of Global Warming

3.4 Sensitivity Analyses

3.4.1 Resources costs & emissions

Motivation & approach

In sections 2.5 & 2.6.1, the difference in value between SBD and ES resources cost c_{op} & carbon intensity gwp_{op} had already been mentioned. Even though the gap between the values may just come from differences in terms of definition and calculation or from generic values in ES for the different case studies, its impact may be of importance. Indeed, it is known that the value of the specific cost and carbon intensity of resources (especially electricity & natural gas) has a significant impact on the results of energy system optimizations. Moreover, their definitions are often subject to discussion, as carbon intensity depends on the consideration and calculation of emissions from production and transport, and as economical parameters might vary depending on the year, the day of the year, the hour of the day and also depending on the scope and who is considered to be paying. In that sense, the definition of cost for electricity & NG might differ between the point of view of the individual consumer for its household consumption and the country's one. Because of intermediaries, taxes and legislation, and depending on how the resource is produced and by who,

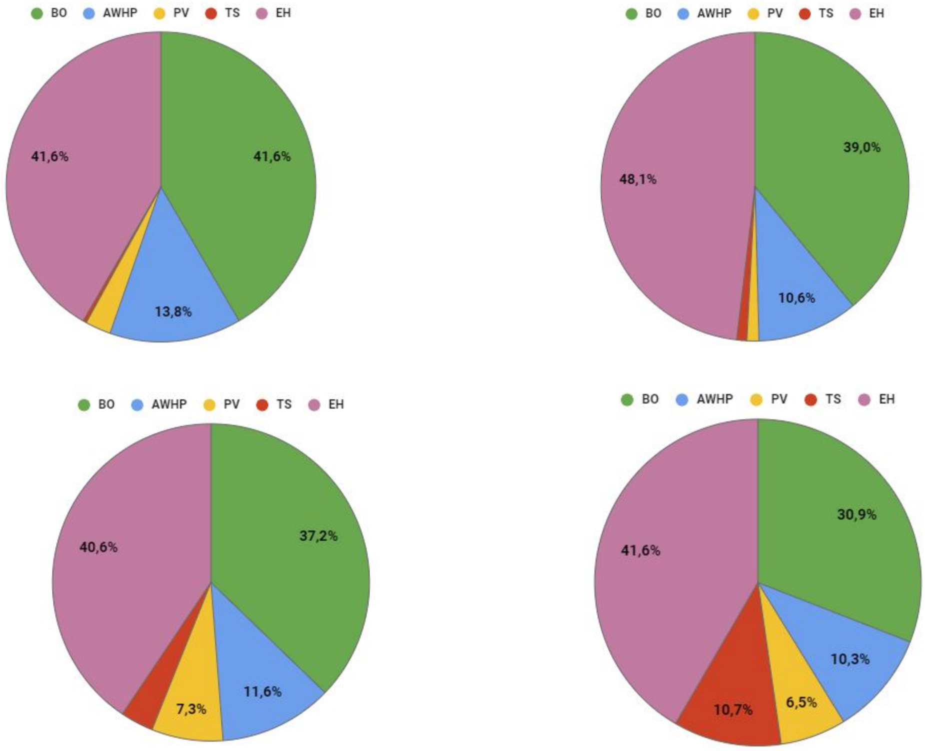


Figure 3.30: Technologies relative installed sizes of the building stock, under TOTEX (top) and GWP (bottom) optimization, with original temperatures (left hand-side) and with consideration of Global Warming (right hand-side)

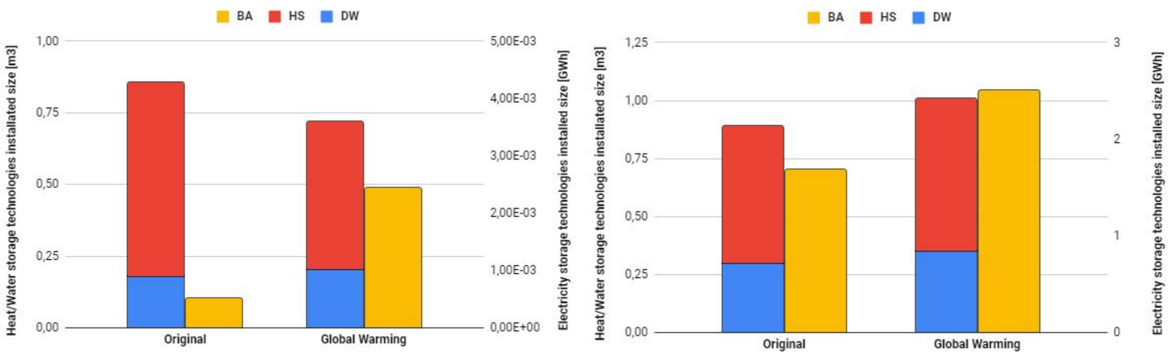


Figure 3.31: Storage technologies installed sizes of the building stock, under TOTEX (left hand-side) and GWP (right hand-side) optimization, with and without consideration of Global Warming

the cost may differ between national-scale and building-scale. Even the total cost in ES might be composed of different costs paid by different entities. The parameters in SBD may be defined and calculated as interaction with the grid, and from costs imposed by energy providers.
Therefore, it is still interesting to study how the results in SBD and ES may vary with different values of resources parameters in SBD. Then, a question arises: how to define the same parameters in ES? Should they be kept as such? It is chosen to leave the costs & carbon intensity of resources defined in ES unchanged and only modify their values in the calculations specific to the building stock. The parameters c_{op} and gwp_{op} will thus be replaced by their values from SBD when multiplied by the resources consumption and production of the building stock (calculated by SBD).

Table 3.2: Resources parameters per model

Model	**Electricity**			**Natural Gas**		
	c_{demand} $[CHF/kWh]$	c_{supply} $[CHF/kWh]$	gwp_{op} $[kgCO_2/kWh]$	c_{demand} $[CHF/kWh]$	c_{supply} $[CHF/kWh]$	gwp_{op} $[kgCO_2/kWh]$
EnergyScope	0.09	0.03	0.48	0.03	0.02	0.27
SBD	0.24	0.08	0.17	0.10	0.06	0.21

Results

Regarding first the costs and emissions of the building stock after optimization of the national energy system, Figure 3.32 illustrates their considerable increase, whether they are induced by the construction or operation of technologies, and for both objective functions.

Regarding the global energy system, Figure 3.33 shows again that the building stock costs and emissions rises, and that its representativeness in the total expenditures and GWP increases as well. Indeed, under TOTEX-optimization, the rest of the system becomes less expensive and carbon-emitting. It is also the case for GWP-optimization, but not for its environmental impact, which rises along with the one of the building stock, yet less consequently.

It is interesting to note as well that, as displayed in Figure 3.34, the MILP then tends to select combinations of scenarios closer to the TOTEX-objective. It also tends to increase the implementation of the renovation option, as depicted in Figure 3.35.
From Figure 3.36, one can see that the energy demand is similarly reduced for both resources under TOTEX-optimization, while electricity supply to the grid increases. On the other hand, under GWP-optimization, the NG demand falls drastically with the SBD parameters, while electricity demand is consequently increased.

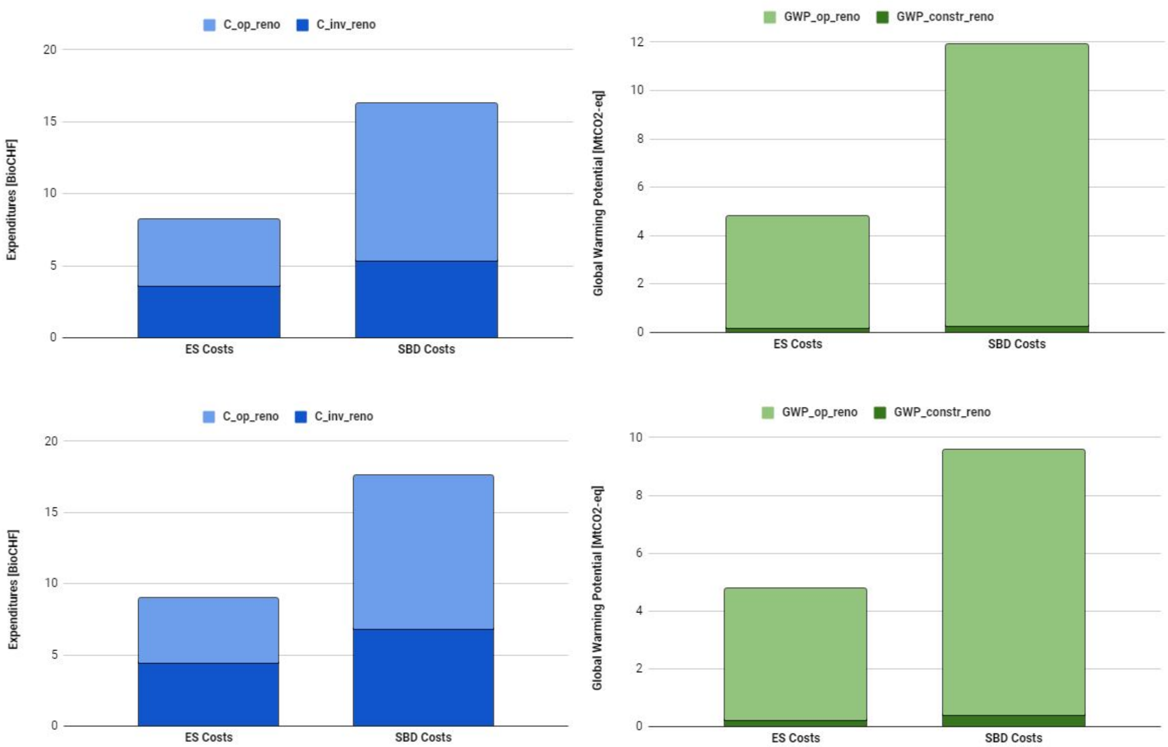


Figure 3.32: Costs (left hand-side) & emissions (right hand-side) of the building stock under TOTEX (top) and GWP (bottom) optimization, with ES and SBD resources parameters

Regarding the technologies installation (illustrated in Figure 3.37), under TOTEX-optimization, the change of resources parameters induces a slight overall increase in capacity of most of them, and particularly of PV-panels. As to the natural gas BO and TS-panels, they are slightly diminished. On the whole, it represents an increased deployment of technologies relying on or producing electricity. Under GWP optimization, the trend is similar, but with much more consequent reduction of BO and increase of PV & AWHP. In parallel, the storage technologies capacity is as well improved, especially for the electric BA, as displayed in Figure 3.38.

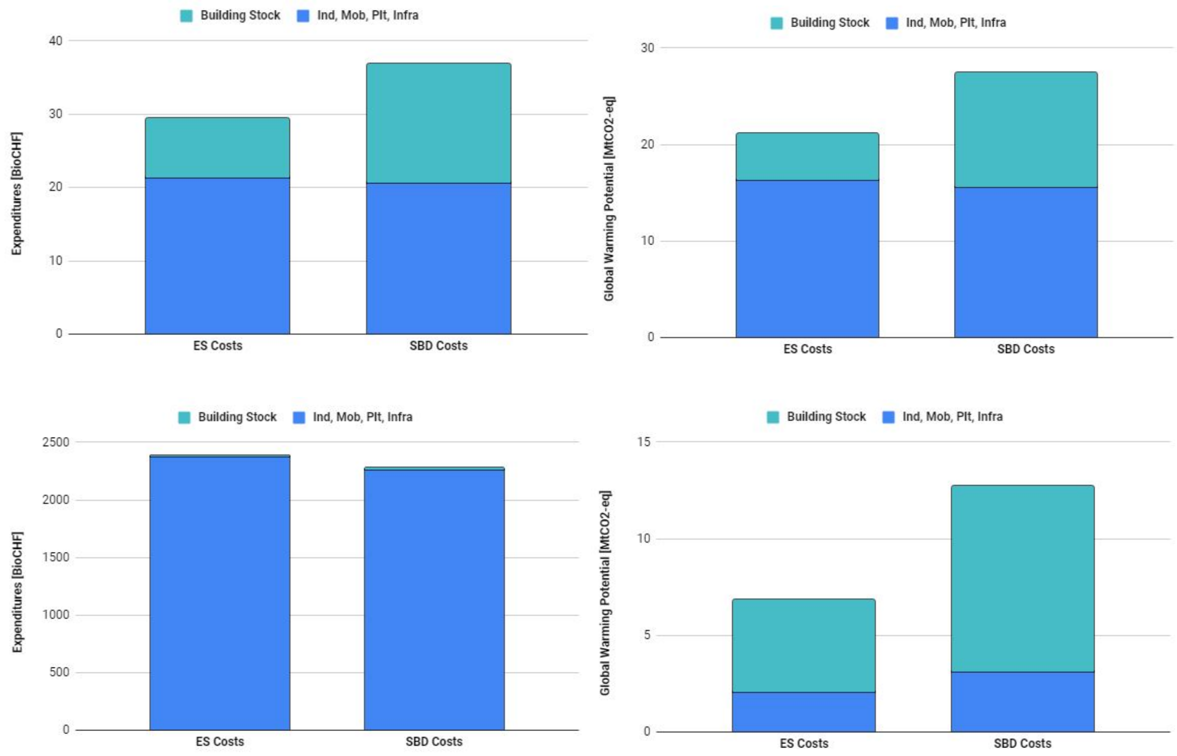


Figure 3.33: Costs (left hand-side) & emissions (right hand-side) of the national energy system under TOTEX (top) and GWP (bottom) optimization, with ES and SBD resources parameters

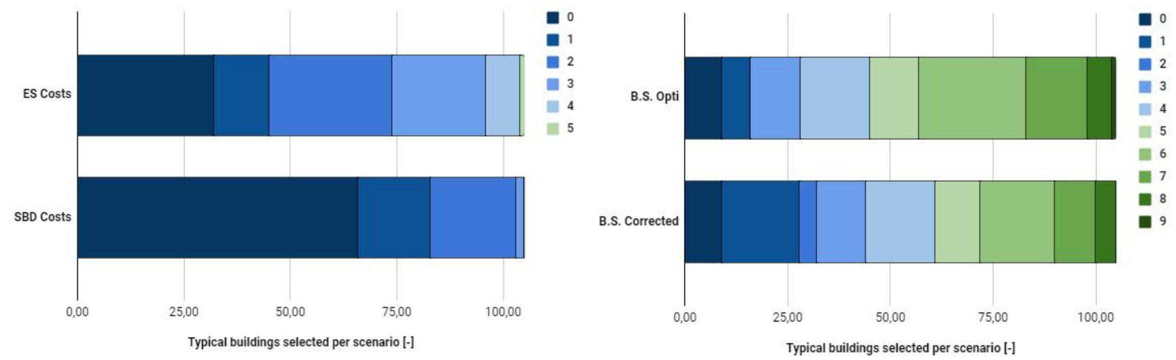


Figure 3.34: Scenario options selection of the building stock, under TOTEX (left hand-side) and GWP (right hand-side) optimization, with ES and SBD resources parameters

3.4.2 Number of scenario options

Motivation & approach

Similarly to the validation approach for selecting the number of nodes in a clustering method (that for example performed in Paul Stadler's thesis [3]), the definition of the number of scenario options from SBD may be discussed, as it may impact both the efficiency of the optimization and the computational time of the whole process. In this section, a quick comparison is therefore conducted,

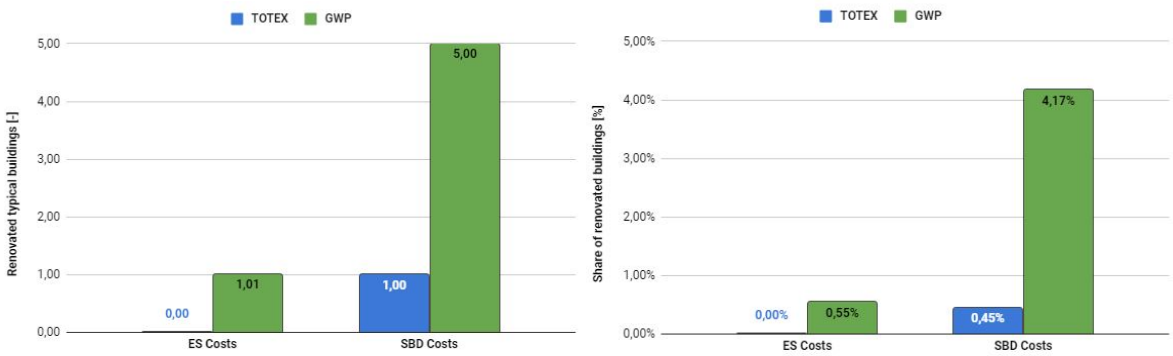


Figure 3.35: Shared of renovated buildings, with ES and SBD resources parameters

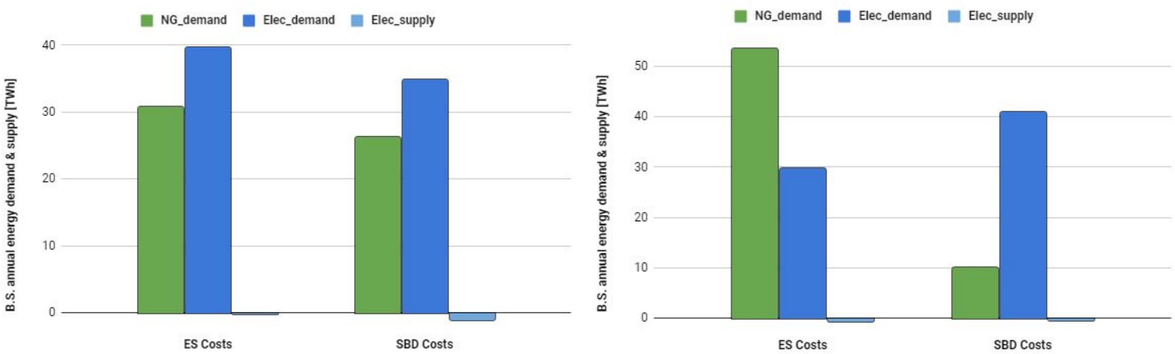


Figure 3.36: Energy demand and supply of the building stock under TOTEX (left hand-side) and GWP (right hand-side) optimization, with ES and SBD resources parameters

between several numbers of scenario options (1,2,5,10).

Results

As for the other comparisons, Figure 3.39 displays the costs and emissions of the total building stock for the different number of scenario options. It shall be noted first that the "1 Scenario" option changes depending on the optimization objective defined in ES, being either a full TOTEX or GWP minimization. It is interesting to note that the total costs and emissions of the building stock do not necessarily decreases with respectively the economical & environmental objectives. Indeed, with an increasing number of scenario options, the TOTEX optimization tends to reduce the building stock total emissions while progressively increase its total cost by oscillating. Meanwhile, under GWP optimization, the two parameters decrease in parallel. This highlight the fact that the most economically or environmentally ideal solution for the building stock is not necessarily the same when considering the whole national energy sytem.

Therefore, the total cost and emissions of the global energy system need to be evaluated for the several sets of scenario options, as well as the relative share induced by the building stock. This is illus-

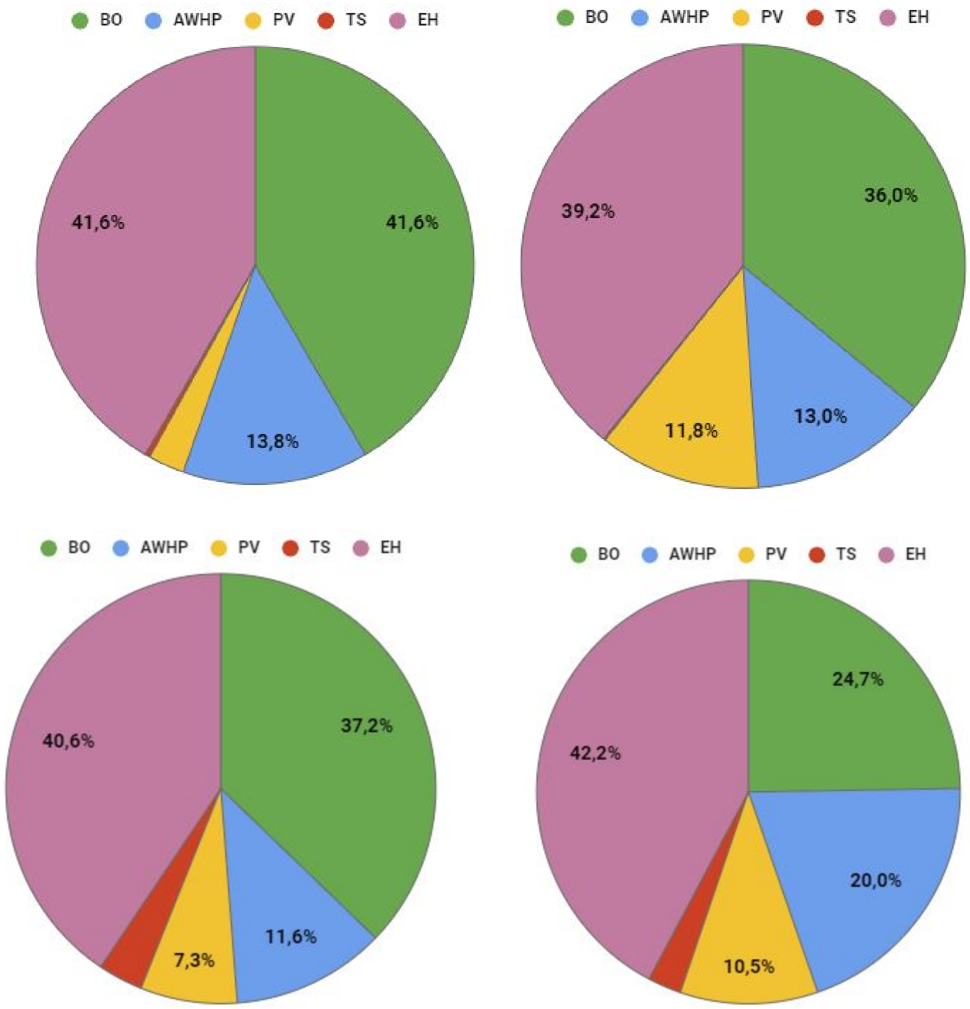


Figure 3.37: Technologies relative installed sizes of the building stock, under TOTEX (top) and GWP (bottom) optimization, with ES (left hand-side) and SBD resources parameters (right hand-side)

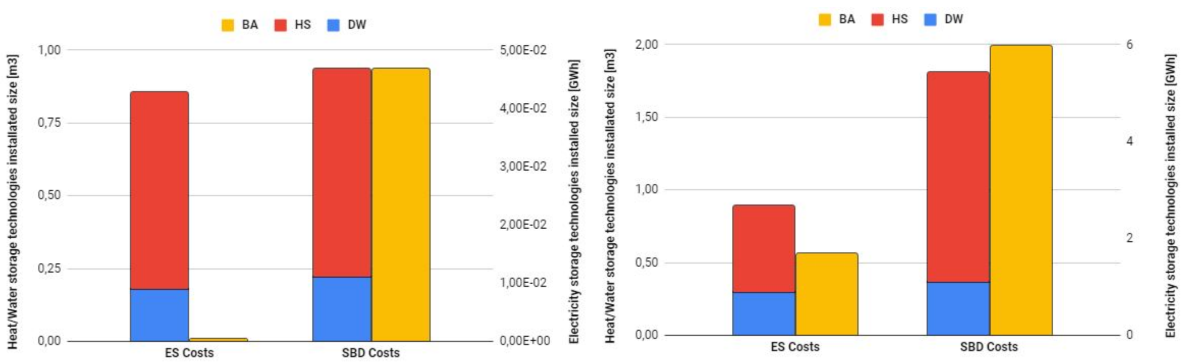


Figure 3.38: Storage technologies installed sizes of the building stock, under TOTEX (left hand-side) and GWP optimization, with ES and SBD resources parameters

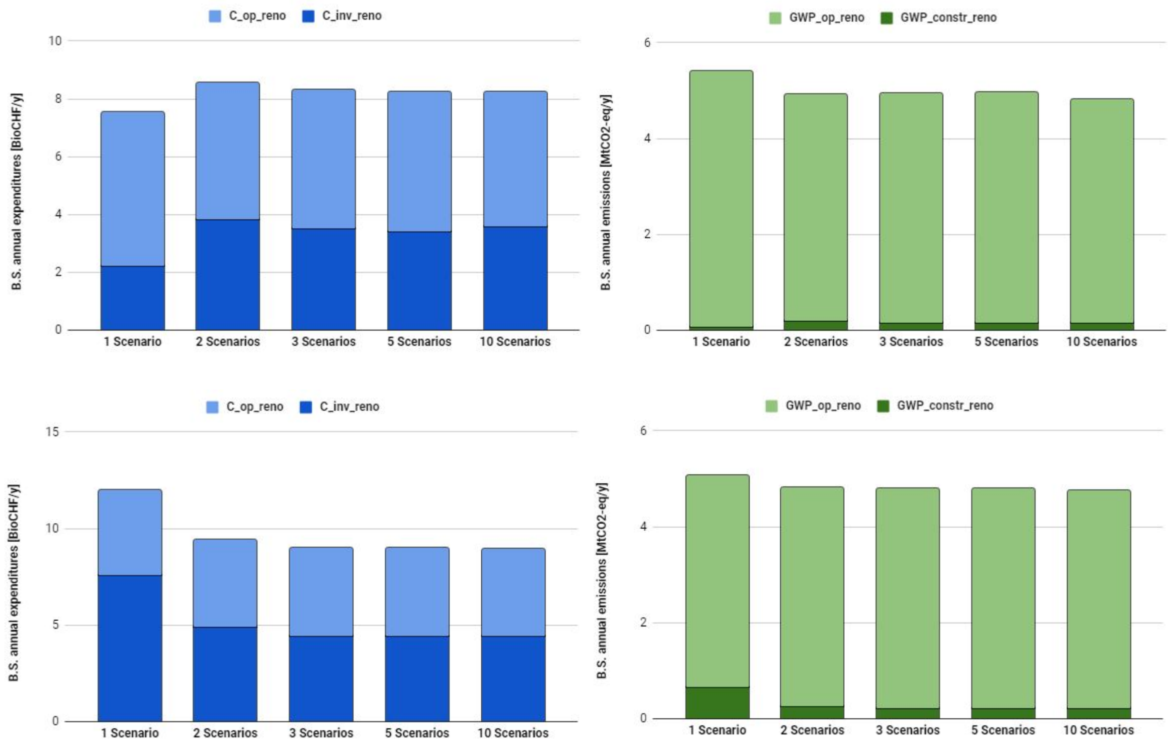


Figure 3.39: Costs (left hand-side) & emissions (right hand-side) of the building stock under TOTEX (top) and GWP (bottom) optimization, for several number of scenario options

trated in Figure 3.40, and it appears that the increased number of scenarios leads to a more optimal solution, as the total cost and the total emissions respectively decreases under TOTEX and GWP optimizations. It can be noted that the improvement of the optimized solution between the different sets of options progressively reduces with the number of scenarios.

Figure 3.41 displays the scenario partition among the building stock for each set and for the two objectives. It appears that the ES MILP always take advantage of the increasing number of scenario options, and particularly under GWP optimization.

Regarding the impact on performance and computing time, Figure 3.42 displays the evolution of the process duration in ES with the increasing number of scenarios. It appears that the process becomes more time consuming with the increasing availability of options, yet that increase is judged acceptable as it is a question of minutes here. However, the impact is was more significant in the SBD process, varying from about $1h30$ to $7h30$ between 1 and 10 scenario options. This considerable computing time is mainly induced by the data management and translation at the output of the step, as the pure optimization process lasts only about $1h30$ for 10 scenarios.

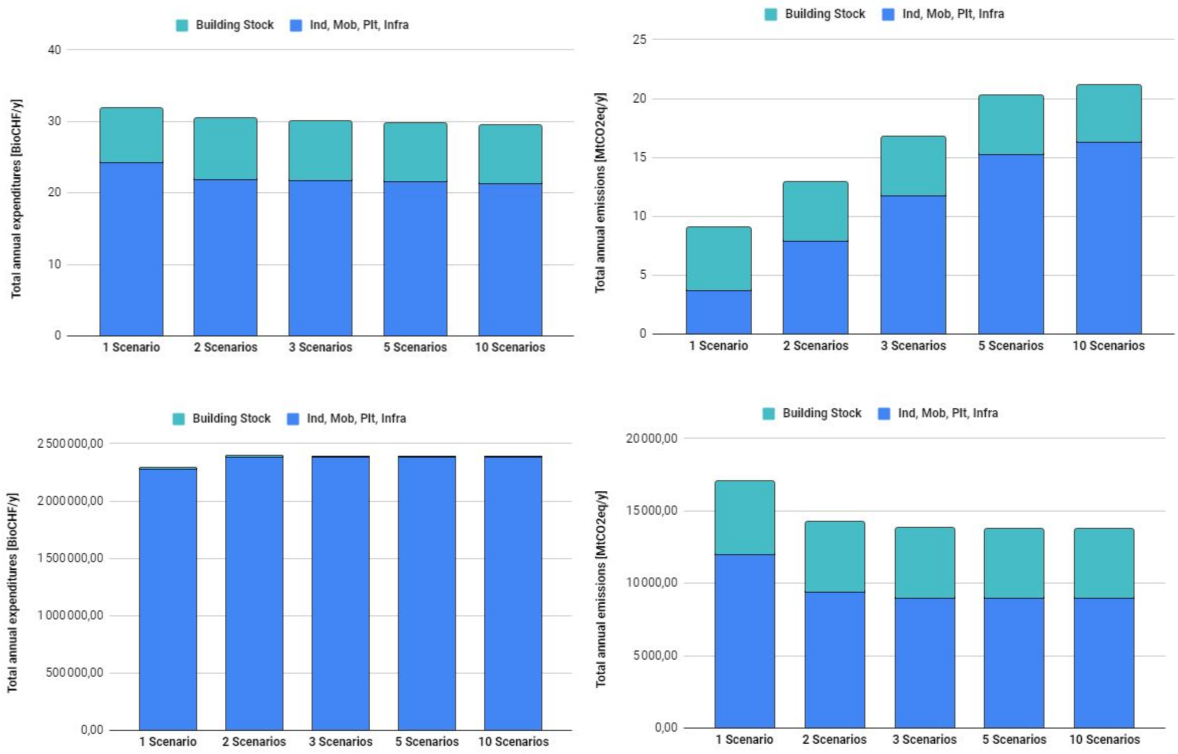


Figure 3.40: Costs (left hand-side) & emissions (right hand-side) of the national energy system under TOTEX (top) and GWP (bottom) optimization, for several number of scenario options

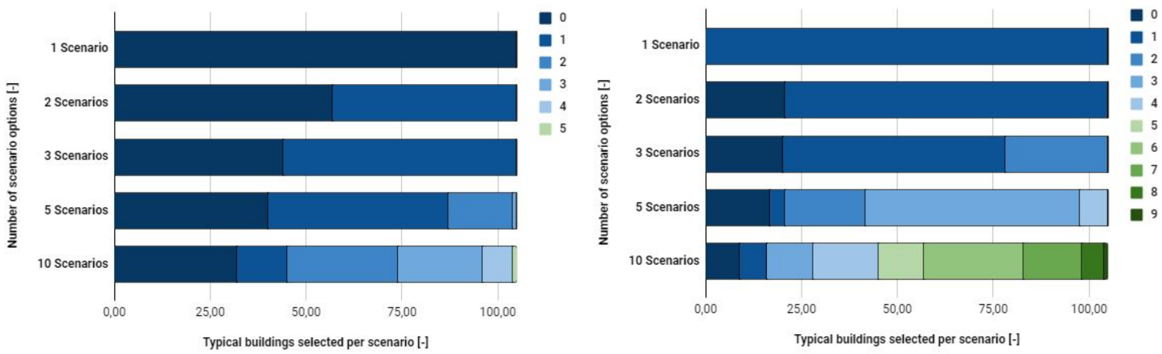


Figure 3.41: Scenario options selection of the building stock, under TOTEX (left hand-side) and GWP (right hand-side) optimization, for several number of scenario options

Finally, Figure 3.43 illustrates the evolution of the renovation installation (in terms of renovated typical building on one side, and of share of total ERA on the other one) with the number of scenario options. First, it shows again that the MILP rather tends to renovated buildings under GWP-optimization. But it shows that it also tends to reduce its implementation with an increasing number of options.

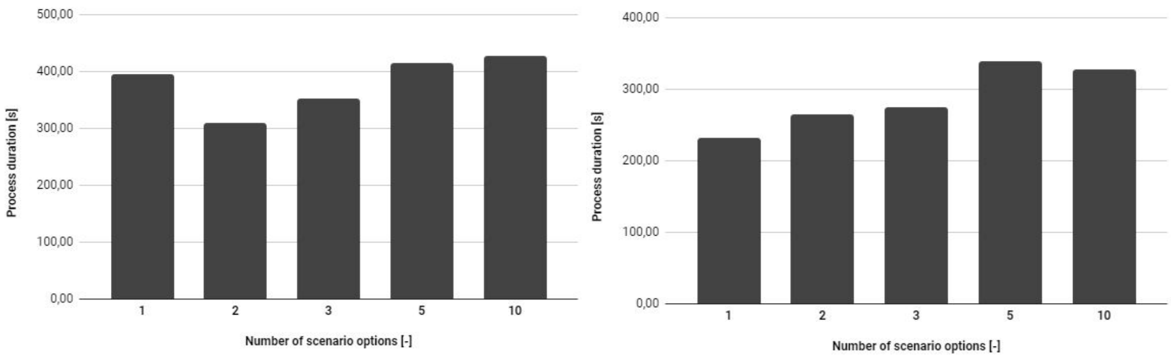


Figure 3.42: Process duration, for several number of scenario options

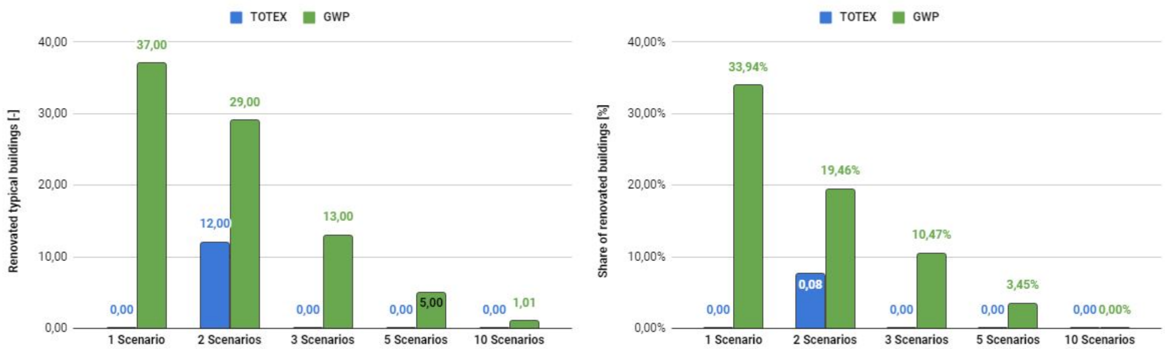


Figure 3.43: Share of renovated buildings, for several number of scenario options

Chapter 4

Discussion

4.1 Results Analysis

4.1.1 Building Stock impact on global energy system

General results

The direct analysis of results from SBD shows a building stock that mainly consumes natural gas under TOTEX-optimization, and that tends to rely more on electricity resource and technologies when improving its environmental impact. The relative capacities of the installed technologies undergo small variations with the objective functions. Indeed, the natural gas BO and EH are kept with consequent capacities in order to match the demand during extreme periods, while renewable energy sources are exploited through the use of AWHP, PV- and TS-panels, the sizes of which increase when minimizing carbon emissions. Regarding the resources' costs and emissions, electricity in itself is here not more interesting than natural gas, but the heat pumps that rely on it are very efficient technologies, and the increased deployment of PV-panels and electric BA allows for self-production and consumption. Indeed, it appears in Figure 3.1 that the building stock tries to reduce its reliance on the grid and thus increases its self-consumption and self-sufficiency in order to reduce its emissions. Electricity supply even decreases with more "environmental-friendly" scenarios, as it takes less into account the potential potential benefit from it and prefers to invest in batteries in order to be able to store and use this energy for itself. All in all, the building stock tends to be more independent from the grid as it tries to be less carbon-intensive, and rather relies on powerful natural gas boilers when trying to reduce its costs.

Regarding the additional features from this new model, the optimization of the building stock within the national energy system in ES offers interesting information. Indeed, the use of scenario options and their granularity as per typical buildings is always exploited by the MILP. It tends to combine options close to the SBD TOTEX-optimization for the same objective, while the GWP-optimization leads to a wider use of different scenarios. The model thus tries to make the most of both the natural gas reliance of the first options, and the low resource consumption of the last ones. It shall be noted also that the last scenario (scenario 9, corresponding to a full GWP-optimization in SBD) is never installed. The handling of the scenario options by the MILP illustrates not only the interest for such a feature, but also the differences in objective and behavior between the two models. Even though it is detailed later, the renovation option already appears to be not very attractive, both from ES and SBD results. Regarding the geographical clusters, it seems that the building stock is mainly impacted by the larger ones in terms of representative ERA, yet that their different behaviors remain interesting and can be analyzed with this new model.

E.S. Comparison

From the results displayed in Section 3, it first appears clearly how the separate optimization of the building stock increases the national energy system costs & emissions. It is also interesting to note that it rather impacts the objective function of the ES optimization, i.e. that the differences are more significant for the total cost under TOTEX-optimization and for total carbon emissions under GWP-optimization. This shows that, with the current configuration, the MILP has less flexibility to optimize the building stock than the rest of the system. It is also shown in Figure 3.11, where the total expenditures and emissions variations between the two objectives are diminished in the current model.

The variations in national- and building-specific technologies between the original and the new model offer an insight of the reasons of this increase. Indeed, as the buildings are optimized individually, considering their own expenditures and emissions, they tend to install local sources of heating and electricity production. When scaled up to the total building stock, it leads to the very consequent capacities described in Figure 3.12. Therefore, and because of the fact that the buildings' interaction is not considered here, the shared resources and infrastructures, like the use of DHN technologies, are reduced. This is particularly the case for the GWP-optimization, where such infrastructures are massively installed, thus drastically increasing the total expenditures to reduce the emissions.

Scaling error

Comparing results between the original and corrected scales allows to confirm the validity of the analysis of the different impacts (of renovation and climatic conditions) and sensitivity analyses. Indeed, it illustrates that the results differ in amplitude of the total costs and emissions, and that the relative share of technologies in installed sizes through the allocation of scenario options varies. However, the energy mix and behavior of the building stock. It also has an impact on the implementation of renovation, yet Section 3.2 shows that it has a very negligible impact on the system. In contrast, the comparison allowed to grasp an interesting characteristic of the geographical clustering on the building stock optimization, in that the weight of each cluster is actually more important than their individual climatic conditions.

4.1.2 Renovation impact on the building stock

The results from the study of the impact of renovation on the building stock are pretty straight forward. Regarding the building stock, the installed sizes of technologies, the resources demand show no visible disparities between the two cases. From the displayed results, it appears that forcing the renovation induces a slight increase of the total expenditures for an even slighter decrease of the emissions, that is not even noticeable here. These results, along with the share of renovated buildings in the other case studies, show that the defined renovation technology has too little impact on the buildings to be attractive for the MILP, even when reduction of CO_2 emissions is the goal. Yet, it is sometimes installed even under TOTEX optimization in both SBD and ES, meaning that it does have an impact and that the model technology is well integrated. In addition, and as seen in Figure B.7, it shall be noted that the renovation option is by definition not available for the entire building stock (84 typical buildings out of 105, representing 92.4% of the total ERA), and that its total impact on the system is therefore limited. However, the scenario selection (inducing the installation or non-installation of the technology) is typical building-specific, and is therefore not influenced by this parameter.

4.1.3 Climatic conditions impact on the building stock

Regional clusters

The results displayed in Section 3.3.1, along with the analysis of the scaling error, bring interesting insights on the impact of regional clustering on the building stock. Indeed, the granularity is by itself a useful tool, not only to specifically characterize each cluster upstream, but also to display and interpret the results per cluster downstream. It also allows to separately optimize each cluster (through each typical building) and observe their differences in resource consumption and production, or in technology installation. The evolution of these parameters can also be studied under several scenario cases. Because of the scaling error, the cluster-specific results are not valid for all of the studied cases here, but this could easily be addressed in the future. But moreover, the analysis of the results allows to compare the total costs and emissions of the clusters as both raw and normalized values. The first ones allow to see how the largest clusters (in terms of ERA) have the most impact, and which ones are the most expensive as per square meter. This particular point may be crucial if considering additional parameters and disparities between the clusters. For example, raw values of the total cost after optimization are interesting for modeling, energy planning and regulations, but the normalized cost directly concerns the household's inhabitants and owners. The behavior of the different clusters between total expenditures and emissions minimization can be easily observed from Figure 3.22. For instance, it highlights disparities between the different clusters that can be visually grouped in 3 or 4 categories. Overall, these groups illustrate the different climatic conditions, with the warmest and sunny cluster $C5$ (Lugano) being the least expensive and carbon-intensive, and the coldest one, $C2$ (Davos), being on the other corner of the graph, i.e. the most expensive and carbon-intensive. However, all clusters in what could be called the "temperate" group do not have similar conditions, with for example $C3$ (Disentis, which has a good average irradiation, yet a low ambient temperature.

All in all, this single graph allows to illustrate differences in characteristics, environmental & economical costs, and, indirectly, in climatic conditions between the different clusters. It is also interesting to look at the shape of the Pareto fronts. Indeed, these dotted curves indicate the potential trade-off options and allow to understand the energy mix evolution along the objective function variations. But their shape also somehow translates the cost of moving from one objective to the other. For example, from the GWP-optimal solution, the total expenditures of clusters C1, C4, C5 & C7 can be easily reduced without impacting carbon emissions too much. On the other hand, from TOTEX-optimal solution, the total emissions of clusters C1, C3, C4, C7 and especially C6 can be consequently reduced with a reasonable increase of costs. In summary, the characteristics and trends of geographical clusters and their building stock energy mix can be somehow understood with such results and figures.

Finally, from the comparison of results between C1 & C7 and the other clusters, and from the scaling error correction learning, it appears that the actual total ERA of each cluster is their most impacting parameter on the total building stock and energy system. However, their climatic conditions do influence their specific consumption and costs, and should not be under-estimated. As said before, the geographical granularity could be further used with additional parameters (indicative or not), such as socio-economic considerations, but also on local differences like resources' costs and carbon-intensity, which could be easily implemented in the current version of the model.

Global Warming

As explained, the lack of consideration for air conditioning leads to an inexact estimation of the global warming scenario, in addition to the fact that not only the average temperature would rise but that also all weather parameters will vary and correspond less to current models. However, this first step still consists in a variation of climatic conditions and do have an impact on both the building stock and the global energy system. As expected, the total costs and emissions of the systems are being reduced by the temperature increase. Indeed, the energy demand is lowered, except for NatGas under TOTEX optimization. This might be explained by the fact that an increased temperature reduces an already low demand for heating in summer, when boilers are switched off. Furthermore, their absence needs to be compensated by other technologies (like Heat Pumps) that, once installed, will keep runnning for the rest of the year and thus reduce the required energy production from boilers. We indeed see that the installation of Heat Pumps and PV panels is decreased. This might be explained as well by the fact that their efficiencies are negatively correlated with the external temperature, which is not the case of TS panels, the installation of which has considerably increased with the ambient temperature.

Even though the temperature increase induces a reduction of the global energy demand, it should be noted that it also reduces the use and installation of two renewable energy technologies. Natural gas becomes even more attractive, and the electricity use and local production are limited by the reduction of PV-panel capacity.
To sum up, variation of climatic conditions does have an impact on the building stock and on the overall energy system, and the current model allows to assess it. It could however be improved by considering additional impacts of global warming and climate change, by implementing air conditioning in SBD and by reporting the modifications in ES, as it would impact technologies and demand for the rest of system too.

4.1.4 Sensitivity analyses

Resource-specific costs & emissions

The results from this analysis show that the modification of resources characteristics does have a significant impact on both the building stock and the national energy system costs and emissions, as well as on the resources demand & production and energy mix of the former.
First, the resulting costs and emissions of both the building stock and the global energy system consequently increase with the SBD parameters, which is not surprising for the economical parameters, as resource-specific costs are much higher in SBD ($c_{op_{elec}} = 0.24$ & $c_{op_{NG}} = 0.10$) than in ES($c_{op_{elec}} = 0.09$ & $c_{op_{NG}} = 0.03$). However, this is quite surprising for the environmental results, as both carbon intensities are lower in SBD ($gwp_{op_{elec}} = 0.171$ & $gwp_{op_{NG}} = 0.214$) than in ES ($gwp_{op_{elec}} = 0.482$ & $gwp_{op_{NG}} = 0.267$), and as the global energy demand from the grid reduces. Actually, in SBD, electricity becomes relatively more interesting than Natural Gas, especially for the GWP-optimization, as it becomes less carbon-intensive and is the resource of very efficient technologies (in the sense of resource consumption) that are PV panels and Heat pumps. The growing installed sizes of such technologies (and diversification of the energy mix), as well as the development of batteries motivated by the intensified dependency on electricity and renewable energies, induce and increase CO_2 emissions related to construction. But it is not sufficient to explain the increase of operational emissions of the total energy system. This can be explained both by the fact that, for the rest of the Swiss energy system, the resources still have the same parameters values in ES. Therefore, the increasing demand for electricity from the building stock enforces its production from power plants and use from imports, and as it is considered more carbon intensive than for the building stock, it therefore has a considerable impact on the resulting emissions. In addition, the scaling error might, in this case have a more considerable impact on the results, as the ERA of the two clusters $C2$ & $C6$ is overestimated, when they happen to be the two most expensive and carbon-intensive clusters and see their electricity demand considerably increase in order to address their specific climatic conditions.
All in all, these results show the considerable impact of the definitions and values of the specific cost and carbon intensity of resources, as well as the need for later additional investigation on the subject and on the translation of point of view when moving from SBD to ES. The difference might partly be explained by the fact that ES takes into account import from other countries (that have more carbon-

intensive electricity production), when SBD has a smaller geographical scope and rather considers local production of electricity.

Scenario options

The analysis of the impact of the number of scenario options on the results shows that it allows to improve the objective function for the national energy system, without impacting the process duration in ES. Indeed, it appears that the MILP always tend to make the most of the available flexibility, as the disparity of selected scenarios considerably increases with the number of options, and especially for GWP-optimization. Except for its total cost under TOTEX-optimization, it also improves the expenditures and carbon emissions of the building stock, even though it is the global energy system that is of concern at this point of the optimization process.
Therefore, the choice to allow for scenario options selection in ES appears to be valid and useful. Furthermore, regarding the evolution of the objectives with the number of scenarios in Figure 3.40, a higher flexibility on the scenario options does not seem to be necessary. It shall be noted that such flexibility considerably impacts the computational time of the SBD process, as it increases from $1h30$ for 1 scenario to $7h30$ for 10. However, this could be considerably improved with better data management and the use of pandas data frames when extracting and translating the SBD results for ES input (which for example represents 80% of the process duration when considering 10 scenarios). Moreover, the SBD step consists in a database creation rather than in a mandatory part of the whole optimization process. Indeed, it is used to create sets of input files for the different case studies and parameters variation, that can then be re-used for multiple optimizations in ES, with different objective functions, constraints and parameters.

4.2 General discussion

4.2.1 Assumptions & Limitations

In the allocated time and with the available data and knowledge, many assumptions and approximations had to be made. First of all, and following the project structure, one could mention the calculations to translate the data from PSD to SBD that sometimes left room for interpretation, thus inducing uncertainty. Some parameters that were not specified were also left as default values in SBD, such as the building envelope heat capacity C_{coef} or the share of available roof. In the second step, the handling (generation & translation) of time clustering could be consequently improved. The reconstruction of typical days specific to each region, for example, does not follow a real optimization and would deserve a more robust and systemic approach. More importantly, the transition from these typical days to the ones of ES at the end of Step 3 has a considerable impact on the representativeness and variety of typical days. When it comes to comparing parameters between SBD and ES, the doubts on the definitions and values of specific cost and emissions of resources adds uncertainty to the results and would deserve an in-depth study. The results generation & analysis brought about another concern regarding the potential for analysis of the impact of climatic conditions on the building stock, as it appeared that the current SBD model does not include cooling or air conditioning technologies. This absence does not allow to study the negative impact of global warming, which then only reduces the energy demand for heating and thus all the expenditures and CO_2 emissions. This point should be addressed to be able to perform a stronger analysis of the impact of climate change, which could be modelled in a more complex manner as well, by increasing the extreme conditions as well as the uncertainty as to weather conditions and thus as to renewable energies' production. Finally, one weak point of this study is that the validation is lacking of historical data to provide a complete and robust simulation of the Swiss 2017 case study, that would allow for more confidence in the model. The results could also be more detailed, yet the automation of the tool and the numerous gathered data already allow for more interpretation of the already available results than what is shown here.

4.2.2 Potential improvement

All in all, these limitations are known, yet the integration between the three models is judged satisfying and successful. It allows for an analysis to be performed and to give some preliminary answers to the research questions. Most importantly, it has been created to be as automatized as possible and allows for later modifications, additional input, and consideration for different building stock clustering and climatic conditions. Along the designing of the model, some thoughts have been raised about the potential improvements that could be brought to it. First of all, with the current in-development features of the SBD tool, consideration of district interactions between buildings (for example connected resource flows and potential for shared installations), if combined with a district-oriented clustering of Switzerland, could represent a considerable enhancement of the model and a very interesting new approach. Regarding the renovation option defined by Paul Stadler, some improvements could be brought with additional work and researches. For example, the lack of CO_2 emissions induced by the installation could be addressed, more details could be added on the features of the renovation (in order, for example, to link it with the Air-Air Heat Pump technology in SBD), and several options (or degrees) could be defined, in order to allow for less expensive intermediary solutions that might render it more interesting for some buildings and regions. This raises the question of the consideration of economic and social disparities within the building stock clustering, which would be as interesting as difficult to assess. Finally, when designing the project structure, the question was raised whether to try to directly implement the building optimization in ES, in order to have a more compact and hypothetically fast process. However, the use of the SBD tool is very promising and judged satisfying regarding the available options and intermediary results. The choice for implementing a set of scenario options in ES rather than a fixed optimized building stock, regarding the results, is also judged worthy and interesting, as the MILP chose most of the time to install different options among the building stock, thus illustrating the actual disparities between typical buildings and regions, that could then be more deeply analyzed.

Chapter 5

Conclusion

In order to address the project's objective, enunciated in Chapter 1, to assess the building stock impact on global energy system, as well as its sensitivity to renovation and climatic conditions, a tool has been designed and presented in Chapter 2. Based on three models of energy system modelling & optimization, developed in the IPESE laboratory, it was developed to be as automatized, independent and adaptable as possible, so as to allow for multiple scenario analyses. Results for a defined case study (Switzerland 2050) under various conditions have thus been generated and displayed in Chapter 3. They have then been analysed and interpreted in light of the research questions in Chapter 4, in order to be able to finally address the project's objective.

Therefore, and from the results analysis (Section 4.1.1), it appears that the building stock has indeed a significant impact on the national energy system optimization, whether it is in terms of total expenditures, GWP or energy mix. Indeed, not only does it represent a large share of the national energy demand, but its separate optimization (performed in this study) tends to lead to higher values of total costs and emissions for the global system. This highlights two important notions and considerations of modelling: the scope of the optimization and the buildings interaction with their environment. These notions arise when comparing the technologies' installed sizes with and without the separate optimization. Indeed, by optimizing the buildings individually, local production is fostered and decentralized units are thus installed per typical building. This, when scaled up to the nation-scale, represents a massive cumulated capacity. The results therefore highlights conflicts between individual and common objectives, but also the lack of district interaction which would allow for shared infrastructures, DHN and exchange of resources.

The separate optimization leads building stock to be considered by the global energy system as a black box with resource flows entering and leaving the sub-system. It therefore offers less flexibility to the MILP than in the original ES model, but also allows for better characterization of the building stock, with granularity on the types of building, the geographical regions and thus on climatic conditions. The hourly heating demand calculation in SBD, from an energy balance based on the building properties and external weather parameters, also allows for consideration of both these climatic conditions and the renovation impact on the building stock. And finally, the typical building granularity combined with scenario options for each of them allows to give back some flexibility to the MILP. This was judged useful and with a reasonable impact on ES computational time from an additional sensitivity analysis (Section 4.1.4).

The renovation option proposed by Paul Stadler [3] was integrated to the model and its implementation share was set as input in order to assess its impact on the building. It appears that the differences in costs, emissions and technologies installation is almost not perceptible between forced and avoided implementation of renovation. The current design of the option leads to very low energy savings, resulting in it being very rarely applied to the typical buildings. The technology modeled in SBD might be re-worked, in order, for example, to allow for gradual levels. Furthermore, its impact on the energy balance and the heating network temperature should be investigated so as to better understand its potential and impact on the energetic system. However, its impact on the total building stock (whether it is before or after integration into the national energy system) is assessed to be very small, yet it does slightly reduce the energy demand and is installed for several typical buildings and climatic conditions.

The impact of the latter conditions on the national building stock was assessed in two steps. First, the results were displayed and analyzed as per geographical clusters. It appears that the type of installed technologies is very similar between all of them, as it rather depends on the units' characteristics (performance, expenditures and carbon emissions), yet that their size and use considerably differ. The study, through a Pareto front analysis of their total costs and emissions, normalized with respect to their ERA, allows to really assess their differences in characteristics and behavior. Switzerland can therefore be divided in three main types of geographical regions, that are more or less expensive, carbon-intensive and adaptable. The cluster granularity also allows to understand their evolution under different conditions, and their normalized parameters allow to understand the impact on the individuals as well. Regarding the impact on the building stock, it appears that the sizes of the cluster and their representativeness in the total ERA is also of great importance. Changes in relative shares of clusters, because of their disparities, can change the building stock's total costs and emissions significantly, as well as its response to climatic variations.
Secondly, such variations were thus applied to the building stock optimization by considering an increase of the average external temperature by +2řC. This modification impacted and reduced its energy demand, total costs and emissions, as well as the ones of the national energy system, but it also impacted the efficiency of technologies like AWHP and PV-panels, reducing the reliance on electricity. This analysis (Section 4.1.3) shows the impact of climatic conditions on the building stock, yet it could be further improved by considering the need for air-conditioning and even other effects of climate change.

Because of the many assumptions, approximations and individual steps, the model presents limitations, but it also has good potential for improvement and especially leaves room for later modifications and consideration of different building stock and geographical clustering, scenario cases and parameters variations, that could allow to deepen the analysis and understanding of the building stock characteristics and behavior, when optimized alone or within the national energy system. One very interesting, yet challenging improvement would be to consider district interactions and potential for DHN during the separate building stock optimization. In the end, the tool would deserve consolidation and improvement, but it addresses the project's objective while having the desired features and allowing for later additional analysis and variations, and it paves the way to really answering the research questions and better understanding better of the behavior and impact of Building Stock within global energy system optimization.

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Appendix A

Methodology details

A.1 Step 1: SBD

Table A.1: SBD input .csv for scaling results

T.B.	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
1	31 280.80	16 723.99	11 946.90	13 671.16	2 431.99	15 842.02	61 731.74
2	68 178.06	24 321.56	18 787.78	26 570.78	9 410.81	25 319.34	164 627.62
3	31 380.05	9 564.90	7 485.75	12 271.38	2 103.83	9 525.95	70 106.68
4	81 948.89	21 587.76	16 013.69	30 247.98	5 756.59	24 635.00	187 629.31
5	24 777.21	7 046.82	5 454.56	7 830.52	1 373.42	8 925.69	47 900.99
6	28 392.20	10 062.45	5 799.28	7 736.12	981.93	11 887.81	44 948.58
7	55 539.67	14 833.70	8 661.35	20 283.01	5 305.67	12 539.49	103 720.81
8	15 209.47	8 470.50	4 536.64	7 209.53	1 836.91	4 671.54	33 279.33
9	29 893.49	13 757.64	7 732.39	13 635.15	2 226.66	9 028.62	70 134.37
10	11 124.04	3 795.56	2 003.02	5 386.27	872.84	3 285.71	28 799.76
11	36 160.51	5 525.31	5 995.58	7 350.72	413.50	13 483.43	56 007.16
12	22 392.42	3 719.22	3 481.66	9 835.08	1 530.55	5 952.69	37 642.39
13	4 101.84	1 490.60	1 106.52	2 868.40	437.60	1 291.76	9 146.77
14	8 310.23	2 404.02	1 887.98	5 214.13	411.35	2 875.84	19 219.74
15	1 196.38	239.98	192.09	648.12	73.40	265.87	3 075.05

Table A.2: SBD input .csv for buildings parameters (Part 1)

T.B.	1	2	3	4	5	6	7	8	9	10
Transformer	”									
RoofUse	0.3									
SolarGainF	0.12					0.03				
Tinto	20									
Ucoef	0.00193	0.00214	0.00204	0.00162	0.001	0.00193	0.00214	0.00204	0.00162	0.001
category	0									
edotel	2.078					2.100				
hs_A	189					505				
hs_{Tro}	50	50	50	50	33.9	50	50	50	50	33.9
hs_{Tso}	65	65	65	65	41.5	65	65	65	65	41.5
n_p	2.244	2.326	2.346	2.363	2.321	6.057	6.317	6.111	6.198	6.349
qdothw	1.393	1.393	1.393	1.393	1.393	1.826	1.826	1.826	1.826	1.826
aff	”									
EGID	0									
$floor_n$	3.15					4.59				
Ccoef	120									
hw_{tech}	1									
$renov_{opt}$	1	1	1	1	0	1	1	1	1	0
$cost_{renov}$	294.02	281.73	277.95	120.58	0.00	294.02	281.73	277.95	120.58	0.00
gwp_{renov}	0									
$Ucoef_{opt}$	0.00094	0.00117	0.00111	0.00121	0	0.00094	0.00117	0.00111	0.00121	0
$hs_{Tro_{opt}}$	44.1	44.1	43.8	45.3	0	44.1	44.1	43.8	45.3	0
$hs_{Tso_{opt}}$	54.4	54.4	53.8	56.3	0	54.4	54.4	53.8	56.3	0

Table A.3: SBD input .csv for buildings parameters (Part 2)

T.B.	**11**	**12**	**13**	**14**	**15**
Transformer			”		
RoofUse			0.3		
SolarGainF			0.03		
Tinto			20		
Ucoef	0.00191	0.00203	0.002	0.00166	0.00107
category			0		
edotel			3.881		
hs_A			558		
hs_{Tro}	50	50	50	50	33.9
hs_{Tso}	65	65	65	65	41.5
n_p	6.866	7.095	7.034	7.071	7.191
qdothw	1.221	1.221	1.221	1.221	1.221
aff			”		
EGID			0		
$floor_n$			3.1		
Ccoef			120		
hw_{tech}			1		
$renov_{opt}$	1	1	1	1	0
$cost_{renov}$	263.93	233.68	243.96	116.59	0.00
gwp_{renov}			0		
$Ucoef_{opt}$	0.00102	0.00123	0.00118	0.00127	0
$hs_{Tro_{opt}}$	44.1	44.1	43.8	45.3	0
$hs_{Tso_{opt}}$	54.4	54.4	53.8	56.3	0

A.2 Step 4: ES

```
## Economic Calculations
#calculation of building stock operational cost with decision variable
subject to C_op_reno_spec:
   C_op_reno = sum {b in BUILDINGS, s in SCENARIOS} (f_s_ID[b,s] * c_op_reno
      [b,s]);

#calculation of building stock investment cost with decision variable
subject to C_op_reno_spec:
   C_inv_reno = sum {b in BUILDINGS, s in SCENARIOS} (f_s_ID[b,s] * c_inv_reno
      [b,s]);

#calculation of building stock total cost
subject to C_op_reno_spec:
   C_reno = C_op_reno + C_inv_reno;

## GWP Calculations
#calculation of building stock operational emissions with decision variable
subject to C_op_reno_spec:
   GWP_op_reno = sum {b in BUILDINGS, s in SCENARIOS} (f_s_ID[b,s] *
      gwp_op_reno [b,s]);

#calculation of building stock construction emissions with decision variable
subject to C_op_reno_spec:
   GWP_constr_reno = sum {b in BUILDINGS, s in SCENARIOS} (f_s_ID[b,s] *
      gwp_constr_reno [b,s]);

#calculation of building stock total emissions
subject to C_op_reno_spec:
   GWP_reno = GWP_op_reno + GWP_inv_reno;
```

Appendix B

Results details

B.1 General Results

B.1.1 Comparison with ES

Table B.1: Comparison of results under Total Cost (TOTEX) and Total Emissions (GWP) optimizations of the Swiss 2050 case study, when using the current model and the original version of EnergyScope. (S.E.S.: Swiss Energy System, B.S.: Building Stock)

	BS-Optimization		**EnergyScope**	
	TOTEX	**GWP**	**TOTEX**	**GWP**
S.E.S. Total Cost [MioCHF]	27 771	2 136 700	20 594	2 156 210
S.E.S. Emissions [ktCO_2]	19 837	5 581	19 428	3 572
B.S. Total Cost [MioCHF]	7 149	8 344	-	-
B.S. Emissions [ktCO_2]	4 176	4 034	-	-

B.1.2 Scaling error

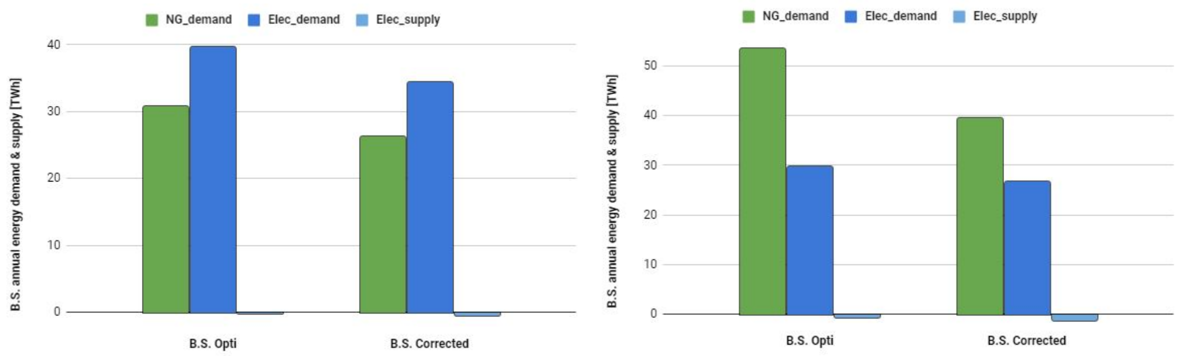

Figure B.1: Energy demand and supply of the building stock under TOTEX (left hand-side) and GWP (right hand-side) optimization, with and without corrected scales

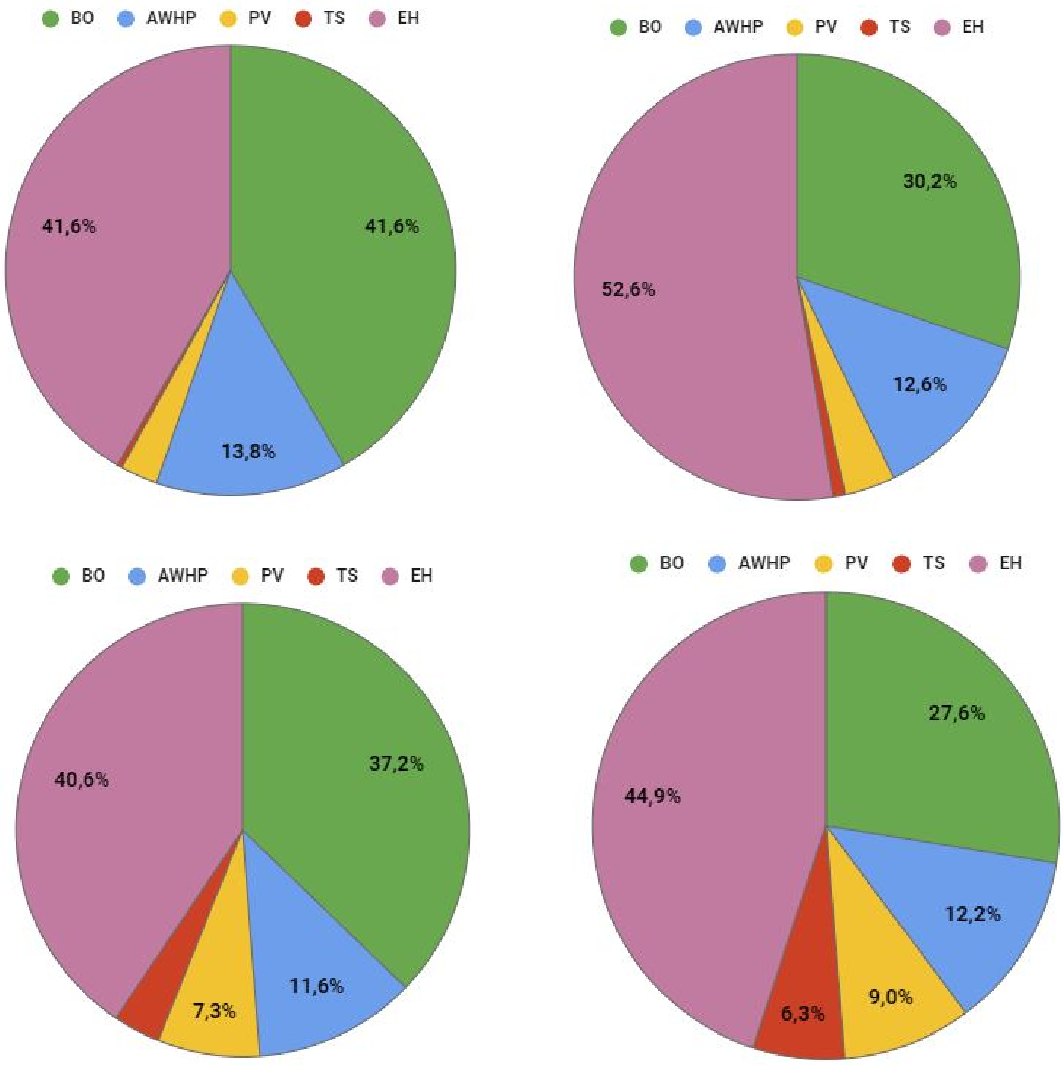

Figure B.2: Technologies relative installed sizes of the building stock, under TOTEX (top) and GWP (bottom) optimization, with original (left hand-side) and corrected scaling factors (right hand-side)

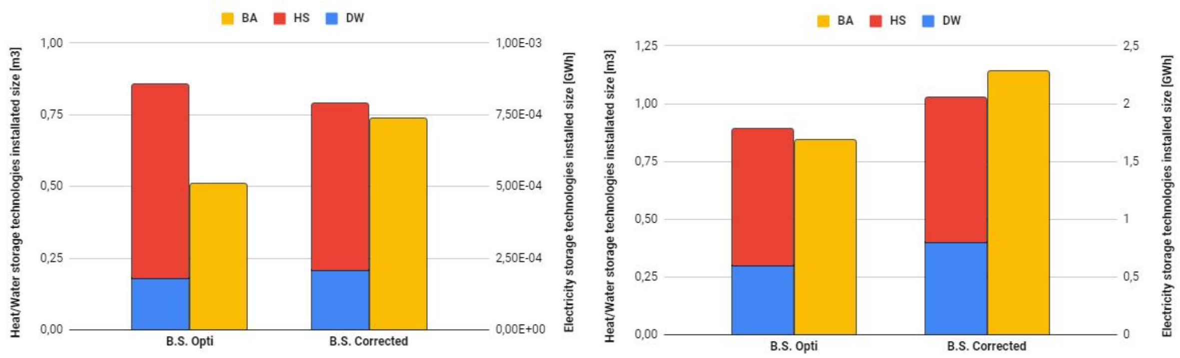

Figure B.3: Storage technologies installed sizes of the building stock, under TOTEX (left hand-side) and GWP optimization (right hand-side), with and without corrected scaling factors

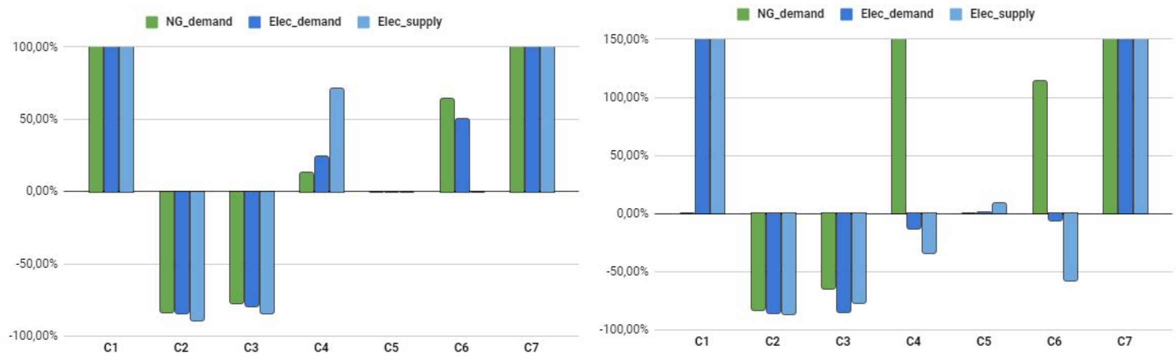

Figure B.4: Clusters energy demand and supply variation between original and corrected scaling factors, under TOTEX (left hand-side) and GWP (right hand-side) optimization

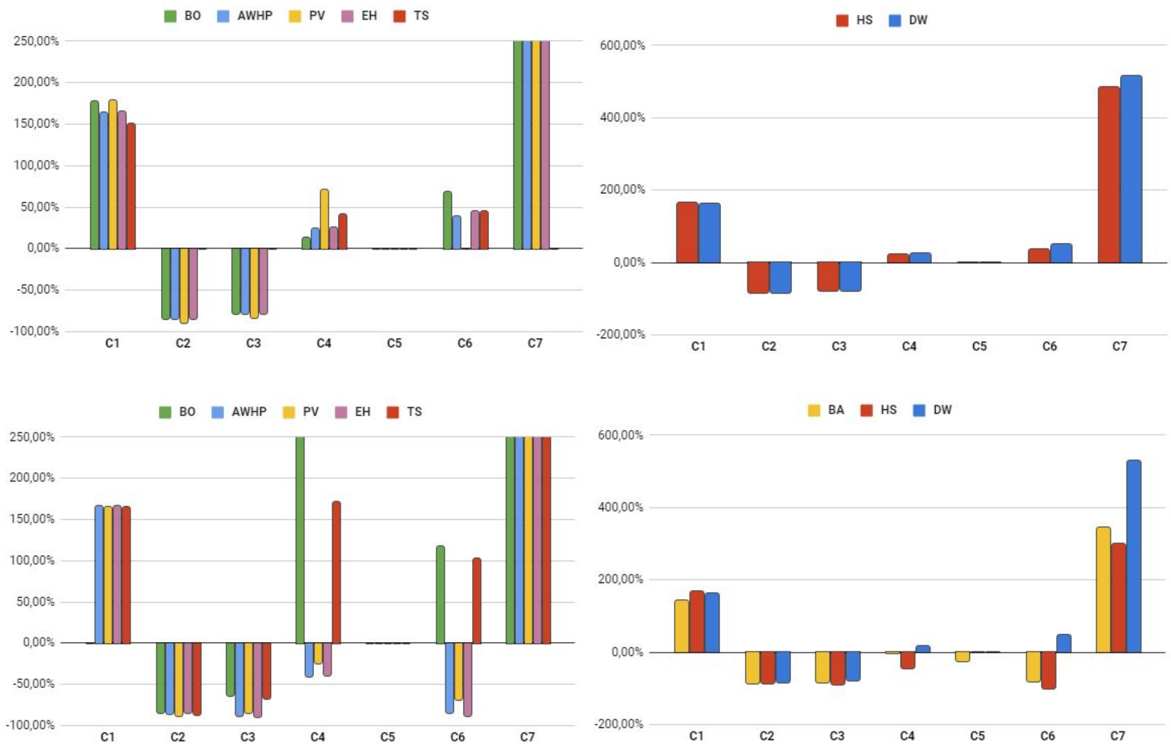

Figure B.5: Clusters installed capacity variation between original and corrected scaling factors, of production (left hand-side) and storage (right hand-side) technologies, under TOTEX (top) and GWP (bottom) optimization

B.1.3 Renovation impact

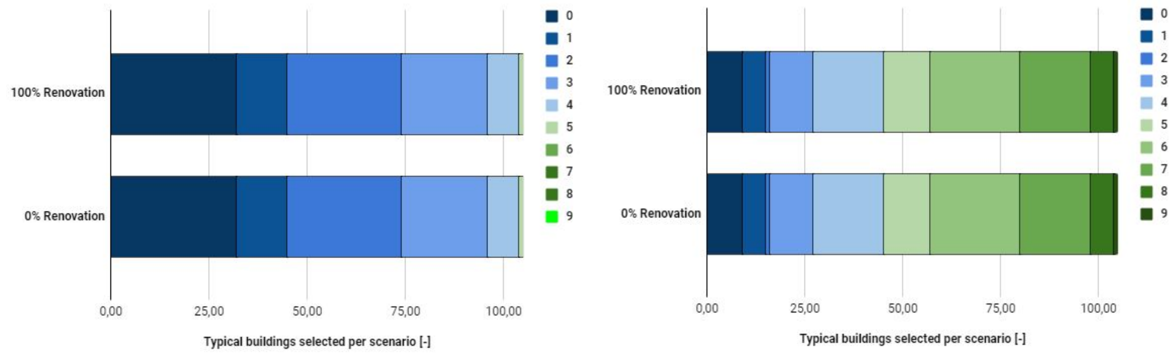

Figure B.6: Scenario options selection of the building stock, under TOTEX (left hand-side) and GWP (right hand-side) optimization, with forced and avoided renovation

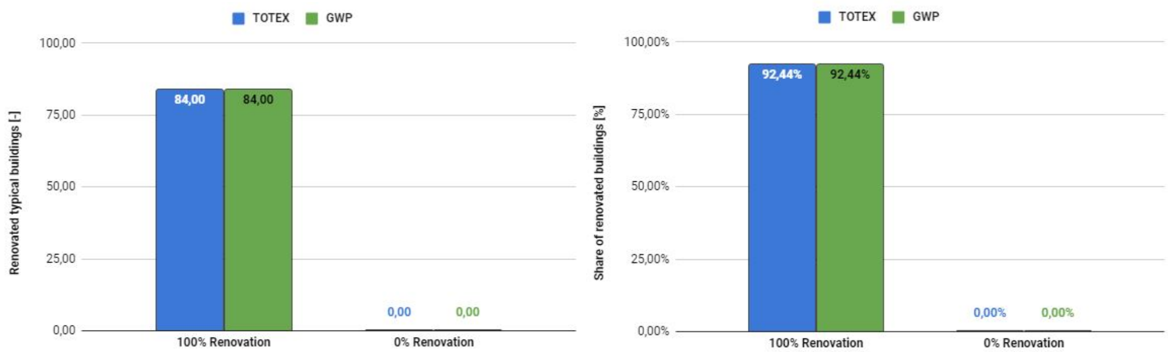

Figure B.7: Shared of renovated buildings, with forced and avoided renovation

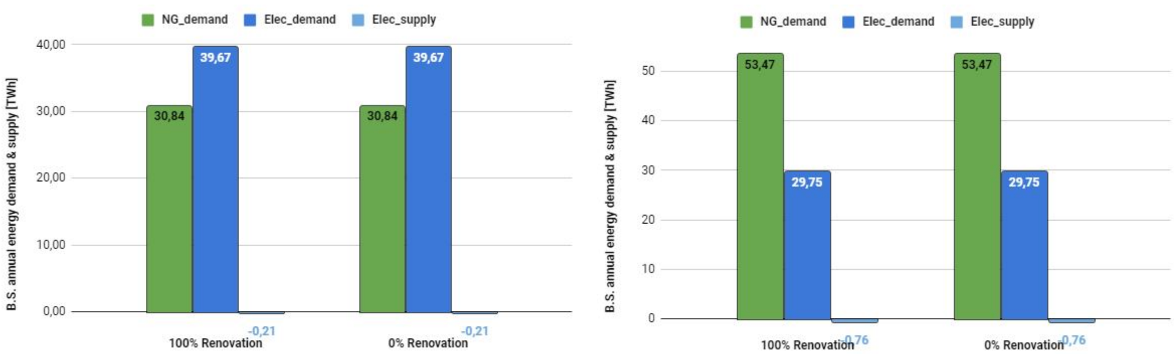

Figure B.8: Energy demand and supply of the building stock under TOTEX (left hand-side) and GWP (right hand-side) optimization, with forced and avoided renovation

B.1.4 Climatic impact

Clusters

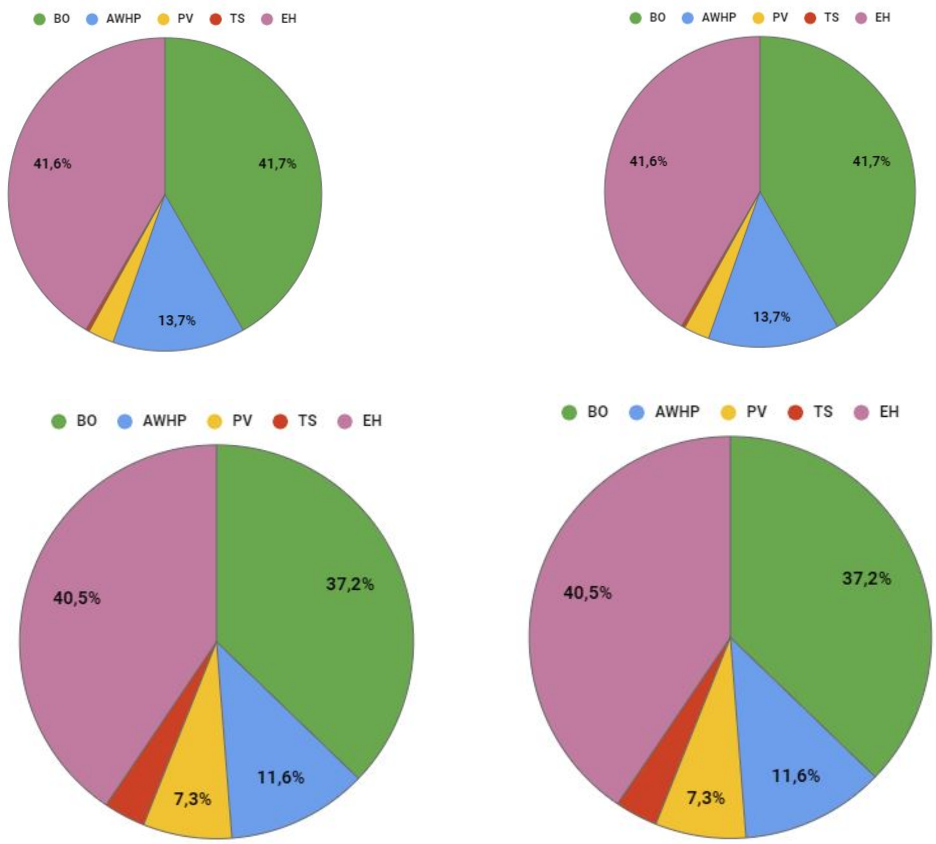

Figure B.9: Technologies relative installed sizes of the building stock, under TOTEX (top) and GWP (bottom) optimization, with forced (left hand-side) and avoided renovation (right hand-side)

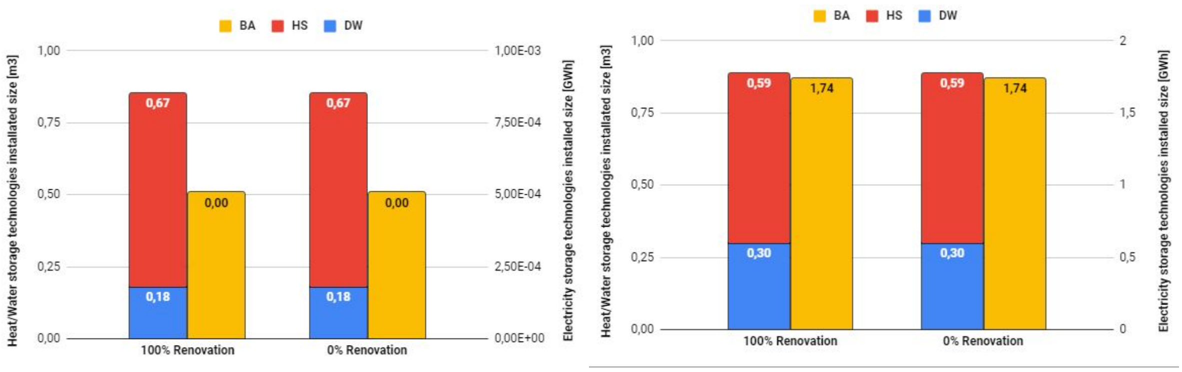

Figure B.10: Storage technologies installed sizes of the building stock, under TOTEX (left hand-side) and GWP optimization, with forced and avoided renovation

B.1.5 Sensitivity analyses

Scenario options

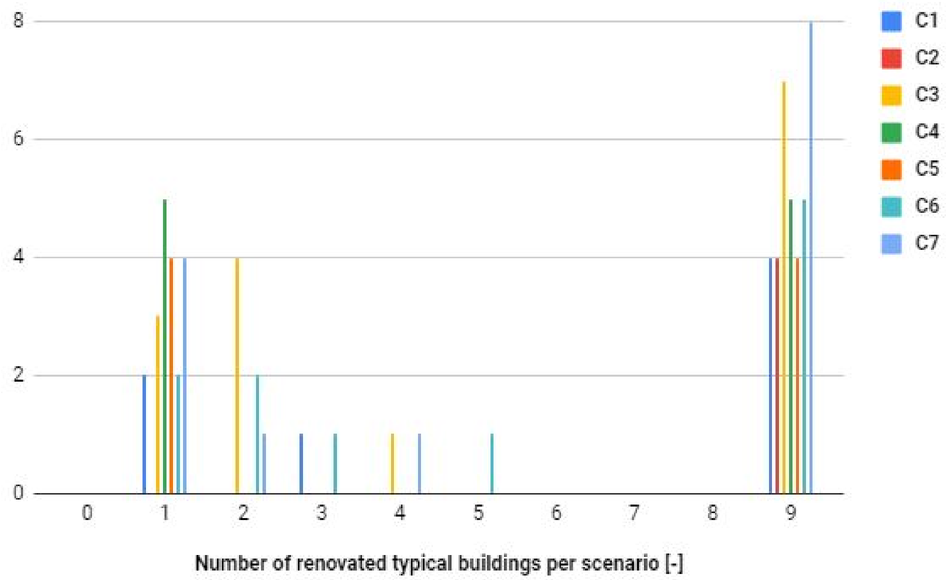

Figure B.11: Share of renovated buildings per cluster and per scenario

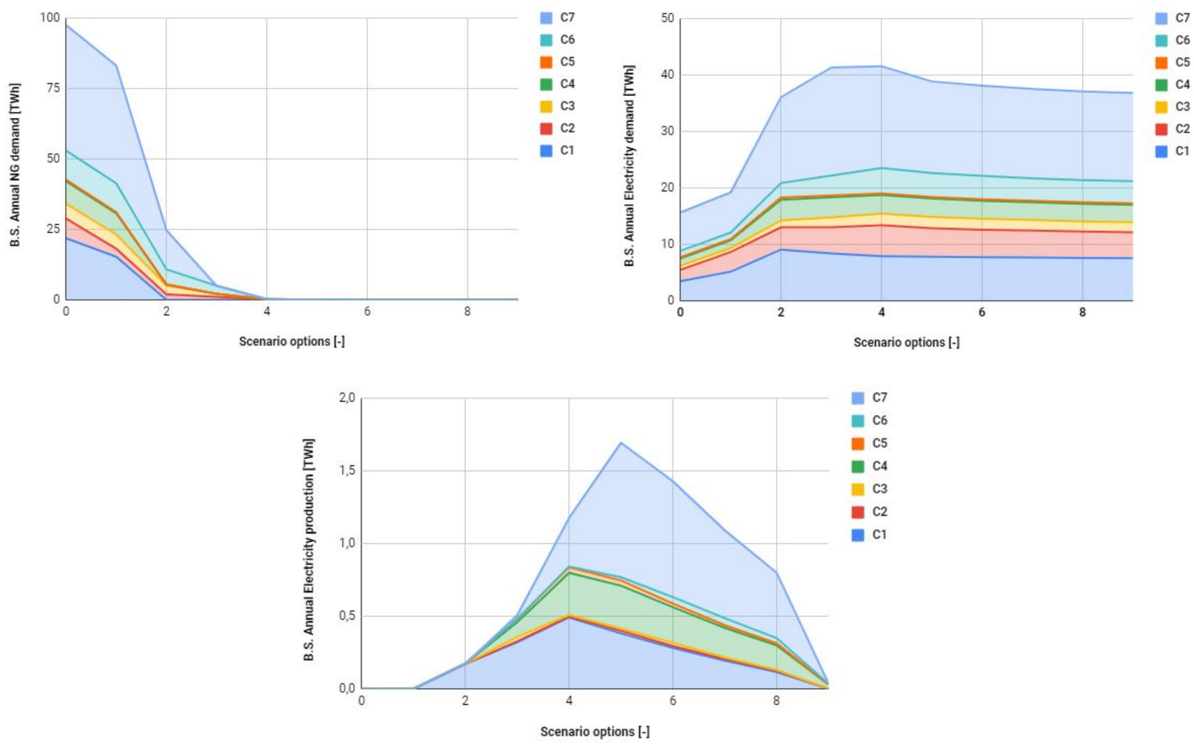

Figure B.12: Cumulative NG demand (top left corner), Electricity demand (top right corner) and Electricity supply (bottom) of the seven clusters, for the 10 scenario options

Table B.2: Comparison of Total Cost (TOTEX) and Total Emissions (GWP) optimizations of the Swiss 2050 case study, with & without renovation. (S.E.S.: Swiss Energy System, B.S.: Building Stock)

	Forced Renovation		**Avoided Reno**	
	TOTEX	**GWP**	**TOTEX**	**GWP**
S.E.S. Total Cost [MioCHF]	29 558	2 382 330	29 534	2 382 300
S.E.S. Emissions [ktCO_2]	21 104	6 854	21 104	6 854
B.S. Total Cost [MioCHF]	8 266	9 000	8 242	8 976
B.S. Emissions [ktCO_2]	4 813	4 765	4 813	4 765
B.S. Scenario selection				
0	32	9	32	9
1	13	6	13	6
2	29	1	29	1
3	22	11	22	11
4	8	18	8	18
5	1	12	1	12
6	-	23	-	23
7	-	18	-	18
8	-	6	-	6
9	-	1	-	1
10	-	-	-	-
B.S. Technologies Installation				
PV [GWe]	1.48	4.26	1.48	4.26
Renovation [-]	84	84	0	0
Boiler [GWth]	22.97	21.77	22.97	21.77
Heat Pump [GWe]	7.55	6.76	7.55	6.76
TS [GW]	0.20	2.00	0.20	2.00
Battery [GWh]	0	1.74	0	1.74
B.S. Energy Demand & Supply				
NG_demand [GWh]	30 836	53 470	30 836	53 470
Elec_demand [GWh]	39 700	29 752	39 700	29 752
Elec_supply [GWh]	213	760	213	760

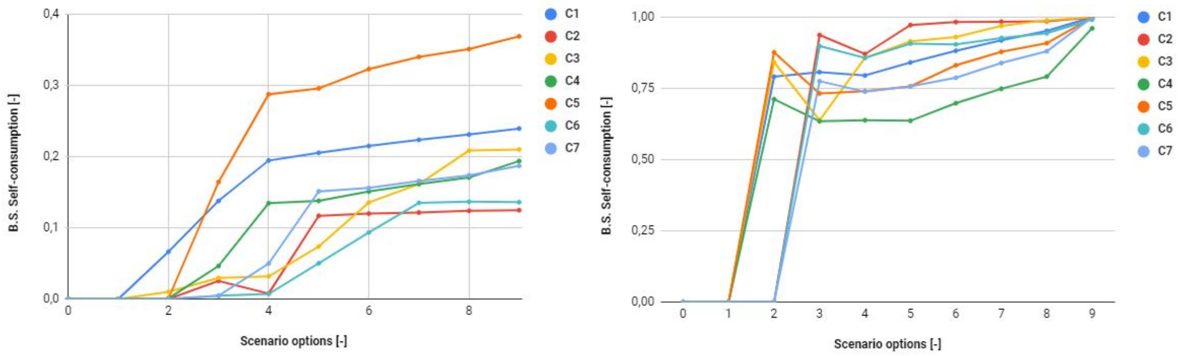

Figure B.13: Clusters self-sufficiency (left hand-side) and self-consumption (right hand-side) evolution with the 10 scenario options

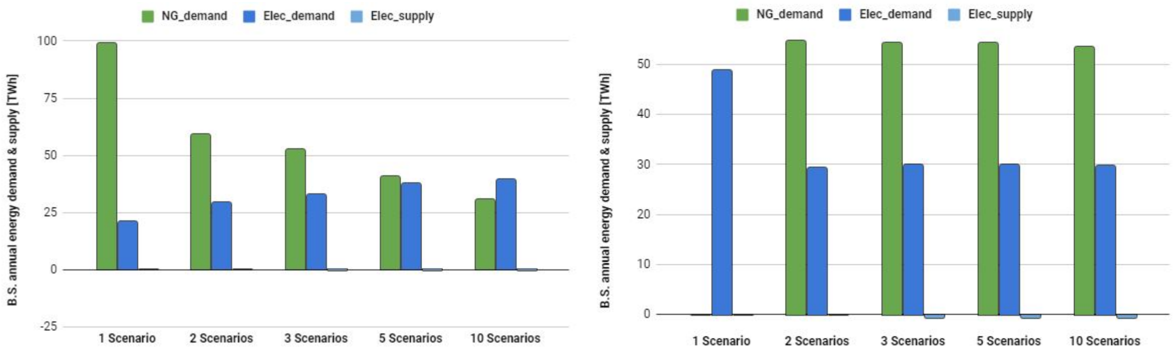

Figure B.14: Energy demand and supply of the building stock under TOTEX (left hand-side) and GWP (right hand-side) optimization, for several number of scenario options

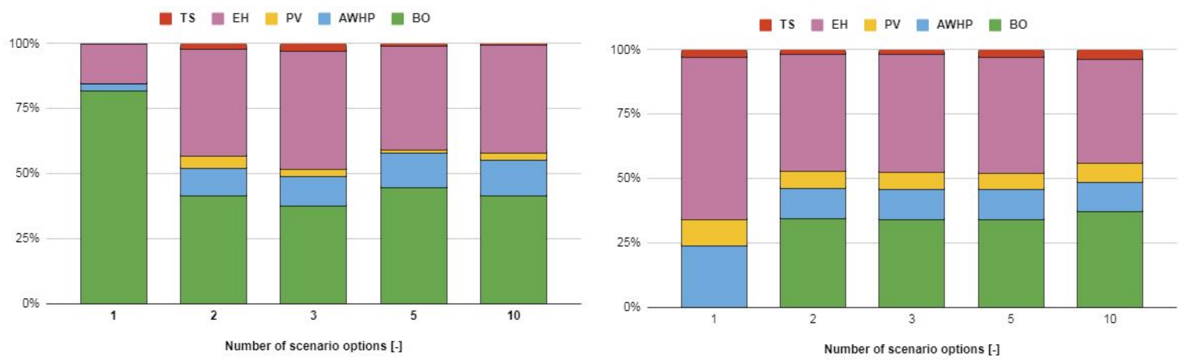

Figure B.15: Technologies relative installed sizes of the building stock, under TOTEX (left hand-side) and GWP (right hand-side) optimization, for several number of scenario options

Table B.3: Results of the Total Cost (TOTEX) and Total Emissions (GWP) optimizations of the Swiss 2050 case study, values for the Swiss Energy System (SES) and the Building Stock (BS)

	BS-Optimization		**Global Warming**		**SBD Costs**	
	TOTEX	**GWP**	**TOTEX**	**GWP**	**TOTEX**	**GWP**
S.E.S. Total Cost [MioCHF]	29 536	2 382 300	28 359	2 381 340	36 897	2 281 400
S.E.S. Emissions [ktCO_2]	21 118	6 856	19 396	6 119	27 516	12 717
B.S. Total Cost [MioCHF]	8 246	8 971	7 335	8 491	16 293	17 646
B.S. Emissions [ktCO_2]	4 813	4 766	4 414	4 343	11 856	9 593
B.S. Scenario selection						
0	32	9	31.08	3.59	66	-
1	13	7	13	6.41	17	-
2	29	0.01	38	4	20	2
3	22	12	16.92	2	2	20
4	8	17	5	17	-	4
5	1	12	-	14	-	3
6	-	26	1	29	-	15
7	-	15	-	23	-	9
8	-	6	-	6	-	49
9	-	0.99	-	-	-	3
10	-	-	-	-	-	-
B.S. Technologies installation						
PV [GWe]	1.48	4.26	0.69	4.20	7.33	7.32
Renovation [-]	0	1.01	0	2	1	5
Boiler [GWth]	22.94	21.76	21.11	19.92	22.36	17.19
Heat Pump [GWe]	7.58	6.77	5.72	6.63	8.06	13.88
TS [GW]	0.20	1.98	0.57	6.89	0.08	1.78
Battery [GWh]	0.00	1.68	0.00	2.50	0.05	5.98
B.S. Energy Demand & Supply						
NG_demand [GWh]	30 734	53 474	35 862	49 773	26 322	10 050
Elec_demand [GWh]	39 700	29 762	33 713	26 413	34 879	41 033
Elec_supply [GWh]	216	767	163	736	1 166	436

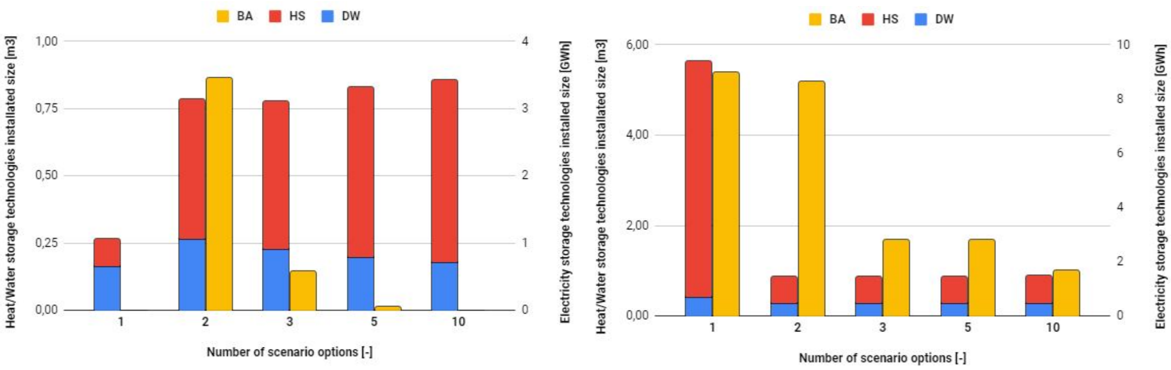

Figure B.16: Storage technologies installed sizes of the building stock, under TOTEX (left hand-side) and GWP optimization, for several number of scenario options