CLIMATE CHANGE IMPACT ON THE DESIGN OF URBAN ENERGY SYSTEMS

G. Mavromatidis[1,2]; K. Orehounig[1,2]; J. Carmeliet[1,3]

1: Chair of Building Physics, Swiss Federal Institute of Technology, ETHZ, Zurich, Switzerland

2: Laboratory for Urban Energy Systems, Swiss Federal Laboratories for Materials Science and Technology, EMPA, Dübendorf, Switzerland

3: Laboratory for Multiscale Studies in Building Physics, Swiss Federal Laboratories for Materials Science and Technology, EMPA, Dübendorf, Switzerland

ABSTRACT

The initial step of the distributed energy system design process is the determination of the energy demand that the system needs to cover. Building simulation is often used for this purpose requiring climate data for the examined period. The long lifetime of buildings corresponds to timescales when considerable changes in the climate are expected to occur. Design using historical or current weather data could lead to underperformance of energy systems that cannot meet future peak loads and/or to the introduction of new demands (e.g. for cooling), considering the long-term impact of climate change. The aim of this work is to firstly investigate the impact of climate change on the loads of buildings for a case study urban quarter in Switzerland and subsequently on the design of the urban energy system to meet the quarter’s needs. Multi-year weather files are created, ranging from 2020 to 2040, using raw data from selected GCMs and carbon scenarios for the examined location using a statistical downscaling technique known as morphing. The optimal design of the urban energy system is obtained using the energy hub concept, examining simultaneously the design (selection and sizing of the conversion and the storage devices) and operational aspects of the system, with minimization of total cost as the objective. Initially, the buildings’ energy demands are calculated for the current and the future climate scenarios and their impact is assessed. Subsequently, optimal energy hub design for the current and future climate scenarios are obtained, and their differences are examined in terms of total cost, but also optimal composition and size of the energy hub. However, since standard practice involves the use of current weather data, the impact of today’s design when operating under future climatic conditions is also assessed. The differences between the operation of the future climate optimised system and the today’s design in terms of operational patterns and resulting costs are examined and any potential hours when the demand cannot be met by the present-day design are quantified.

Keywords: climate change, morphing, weather files, energy hub

INTRODUCTION

Buildings are a major contributor to anthropogenic greenhouse gas (GHG) emissions that are considered the main driver of climate change. The adoption of distributed generation technologies in order to transform building and urban energy systems into sustainable entities can curb emissions and contribute towards the mitigation of climate change. However, given that a degree of future climate change is now inevitable regardless of mitigation efforts, buildings will also have to operate and adapt to the future climatic conditions.

Buildings are long lasting structures, and they are expected to function properly for decades, meaning they are particularly at risk from climate change. Climate change is expected to affect buildings’ differently, depending on the location. The main impacts can be summarized as a shift in energy use via a decrease in heating energy demand and an increase in cooling demand. Other impacts, according to [1], include a shift in thermal operational conditions of equipment that could lead to passive/natural systems going out of range or HVAC capacity mismatch for the heating and cooling peak loads, resulting in inefficiencies. Thus, the energy systems installed should be designed considering the future climate in order to be able to supply the buildings with the necessary energy services ensuring a comfortable indoor environment.

In the building energy design process, the first step that building and system designers need to take is to evaluate the buildings' energy demands. This task is usually performed using Building Performance Simulation (BPS) tools that use weather files to represent the climate that buildings are exposed to. The current status quo practice includes the use of weather files generated using past weather data. However, climate conditions due to climate change are expected to be different compared to the previous years; thus there is always a risk of an ineffective design leading to bad energetic and economic performance of the system.

Climate change impacts on the building stock's energy consumption and GHG emissions has been the topic of several publications, ranging from country scale investigations (*e.g.* [2]) to specific building case studies (*e.g.* [3]). Moreover, the scope of the studies is not always energy consumption, but studies have also focused, for instance, on thermal comfort aspects [4]. The objective of this paper is to take the next step and investigate how the changes in energy consumption patterns are reflected upon the optimal energy system design. The differences between the optimal designs obtained for the current and the future climate are assessed and the shortfalls of the operation of today's design under future climatic conditions is analysed.

METHOD

Climate change weather files

The first step of the methodology is the generation of weather files that reflect the future climatic conditions. In order to model the global climate, General Circulation Models (GCM) are used in conjunction with Representative Concentration Pathways (RCPs), which denote the cumulative measure of human GHG emissions from all sources. In this work, climate change data have been obtained from the Coupled Model Intercomparison Project, Phase 5 (CMIP5) coordinated by the World Climate Research Programme (WCRP) [5] that have also been the basis of IPCC's fifth assessment report [6].

However, a well-known problem with using the output of GCM models is that they have very coarse spatial (~100-200 km) as well as temporal (typically monthly) resolution. Therefore, in order to use their output with a building simulation software, a technique is needed to downscale the data to the examined location and at the desired, hourly resolution. In this paper, a statistical downscaling approach is used called *morphing*, as introduced by Belcher et al. [7] is used to obtain hourly weather data. The technique transforms present-climate weather files into future climate change weather files by shifting the data to adjust to the future monthly mean of the examined weather variable, applying a stretch to match the monthly variance or a combination of both.

In this work, climate change weather files are created for two different GCM models, namely the *GISS-E2-H* and the *GFDL-CM3*, and two RCPs, namely *rcp45* and *rcp85*, representing an intermediate and a high emission scenario, respectively. Moreover, similarly to the work of Robert and Kummert [8], individual future years for the period of 2020 to 2040 are created to preserve some year-to-year variability and thus the extremes that can be observed during the projected operation of the urban energy system.

Case study

To illustrate the methodology and the impacts of climate change on the optimal energy hub design a case study urban neighbourhood is considered consisting of three buildings of different types, namely an office building, a restaurant building and a multi-family residential building. The buildings' energy demands for heating, cooling and electricity services are calculated with *EnergyPlus* using the generated future weather files for the climate of Zurich, Switzerland.

Energy hub model

For the case study selected, the energy system design is performed using the energy hub model [9]. It is used to select the optimal components, their capacities and calculate their optimal operating schedule. For the case study considered in this paper, the energy hub representation can be seen in Fig. 1. The candidate system is composed of a natural gas fired boiler and a CHP engine for the supply of heating services. For the cooling needs of the buildings, a conventional electric chiller and an absorption chiller are included. To allow flexible usage of the devices hot and chilled water storage modules are added. Finally, the electricity demands of the buildings can be covered by the CHP engine, while connection to the national grid is also maintained.

The objective of this energy hub study is the minimisation of the total cost of the system, composed of the investment required to purchase the equipment and the operation cost during life time of the equipment. The model formulation follows the typical energy hub structure, as presented in other publications (e.g. [10]). This means that the constraints included in the problem are energy balances for the different energy services and the operation of the storage systems, non-violation of maximum capacities for conversion devices and storage during operation, maximum possible storage capacities due to space limitations, and minimum part loads for the operation of the conversion devices.

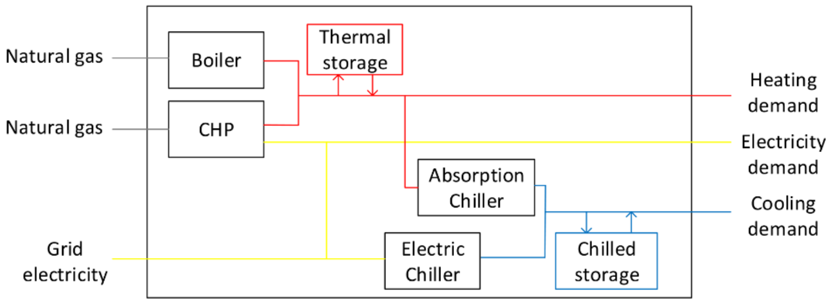


Figure 1: Energy hub representation of the urban energy system considered in this case study

In this paper, the energy hub model is used to perform two different calculations. Initially, the model is run to obtain the optimal energy hub design using the energy demands of the buildings calculated with today's weather and for each climate change scenario considered. The second calculation stream consists of calculating only the optimal operation schedule of the design obtained with today's weather but under the future energy loads change in order to investigate any potential shortfalls in its performance.

Due to the mixed-integer formulation of the problem, performing the design of the energy hub considering all the hourly steps that it is expected to operate (8760h for the current climate and 20 years in hourly steps for the climate change scenarios) would make the problem intractable. For that reason, a two-step approach is considered. Initially, for the considered operational periods, a set of typical days is created following the approach by [11], and the hub's design problem is solved for these typical days only. After the optimal components of the energy hub and their capacities are calculated, they are fixed to their nominal values and the operational schedule is calculated for the complete period.

RESULTS AND DISCUSSION

Climate change impacts on buildings' energy demands

The first step, as was discussed earlier, is the calculation of today's heating and cooling demands using the present-day weather file and for the climate change scenarios during the 20-year period considered. The variation of annual heating and cooling demands against today's benchmark value is presented in Fig. 2.

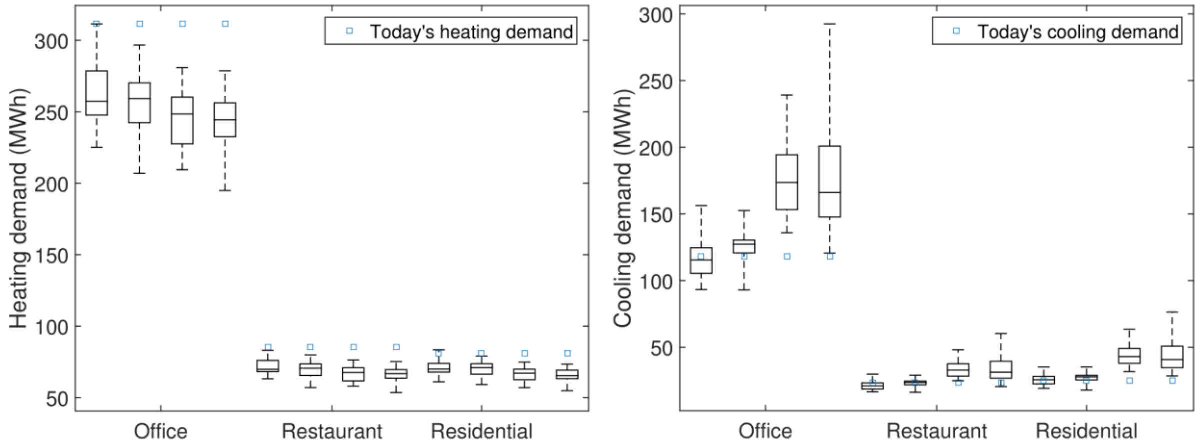


Figure 2: Variation of annual heating and cooling demand of the buildings for the current and the future climate. The four box plots per building correspond to the different models used in the analysis (GISS-E2-H-rcp45, GISS-E2-H-rcp85, GFDL-CM3-rcp45, GFDL-CM3-rcp85).

Regarding the heating demand, it can be seen that for all buildings, the level of energy requirements calculated for today's climate is higher for the majority of the years for all models considered. On the contrary, the mean annual cooling demand for all buildings and for the first two climate change scenarios seem to be relatively close, even though the boxplots' ranges show that there can be warm years when the annual cooling demand is significantly increased. The situation is reversed for the two latter climate change scenarios, where it is seen that the increase in annual cooling demand for all buildings is more dramatic, with the cases of the office and the residential building having for all 20 years, in both models, demands that are higher than the ones calculated with the present climate data. Finally, it can be seen that there is significant difference between the cooling demands predicted by the two different models considered (*GISS-E2-H* and *GFDL-CM3*), but the difference between the two carbon scenarios (*rcp45* and *rcp85*) using the same model is not substantial for the future horizon considered.

Climate change impact on optimal energy hub design

The next step is the comparison between the optimal energy hub designs for today's climate and the future climate scenarios. The variation of the capacities of the elements selected and the resulting investment cost are shown in Fig. 3. It can be seen that in today's design, under the current climate, a simple configuration for the energy system is selected. The CHP engine and the absorption chiller are excluded from the design and only a boiler and an electric chiller are selected. On the other hand, the designs of the climate change scenarios include all possible components. Compared to today's design, the boiler is sized lower for all scenarios and the chiller's capacity is smaller for the first two and larger for the latter two scenarios. Additional heating and cooling capacity are also added in the form of the CHP engine and the absorption chiller. Finally, in all configurations the thermal and chilled storage capacities are maximised and equal to the maximum allowable due to space availability constraints.

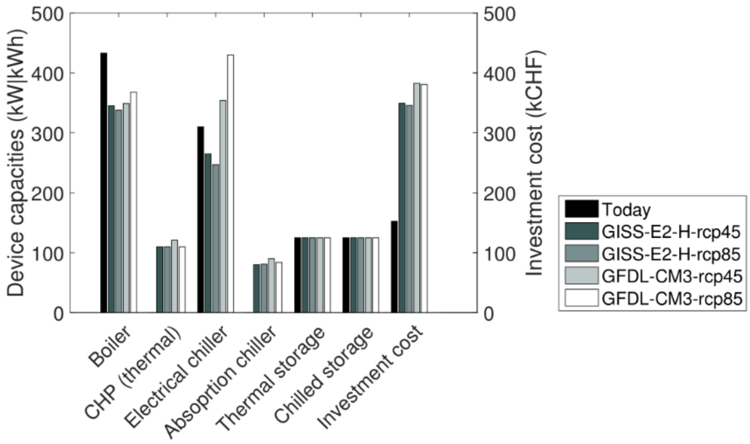
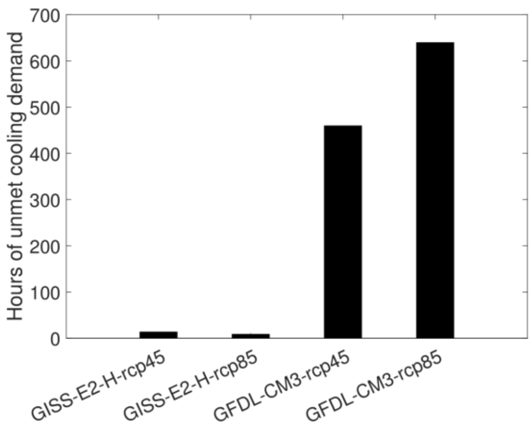


Figure 3: Variation of optimal energy hub design for the current and future climate

The final results discuss the operation of the hub design obtained with today's climate under the future loads. In Fig. 4a, the number of hours that the cooling demand cannot be met for each scenario due to lower installed cooling capacity are presented. For the first two scenarios, the number of hours is limited, due to lower impact on the demands predicted by the GISS-E2-H GCM. However, for the second GCM considered, it can be seen that the number of hours during the lifetime of the system ranges from more than 400 hours to above 600 hours.



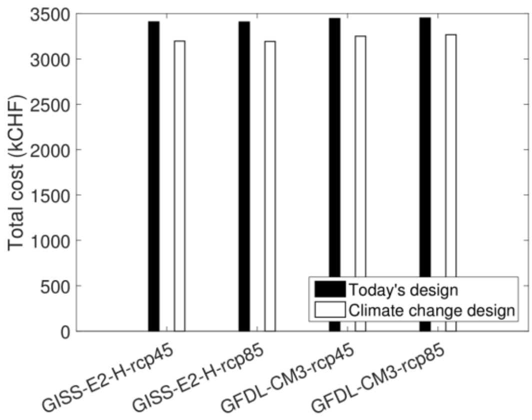


Figure 4: a. Number of hours that today's energy design cannot meet the cooling demand for the future climate scenarios. b. Total cost comparison between the energy hub design obtained with today's climate operating under climate change and the optimal designs for each climate change scenario.

More importantly, though, Fig. 4b presents the total cost of the system when operating under the future loads against the optimal design for each particular case using the future loads. It is seen that in all cases costs are much higher, even though for all cases the investment costs are larger, as presented in Fig. 3. The reason is that the energy hub design obtained when considering the future energy demands is specifically optimised for the future's climate conditions and thus an increased investment cost is compensated by a much lower operating cost. Therefore, not considering climate change when designing an energy system can lead to suboptimal designs both in terms of demand coverage but also in cost terms.

CONCLUSIONS

This paper deals with considerations of climate change and the design of urban energy systems. Initially, it can be seen that even for a few years into the future (2020-2040) the use of weather files built upon past data can lead to an overestimation of heating and an underestimation of cooling demands for buildings. Extending the investigation on the impact on optimal energy hub design, it became evident that firstly the components selected change as well as their capacities. Moreover, the system design obtained with the current weather file underperforms when subjected to the future energy demands leading to hours of unmet cooling demand, but also a higher total cost compared to the climate change optimised system designs, even though the latter ones have higher investment costs.

As future work, the incorporation of additional models from CMIP5 and projects with higher spatiotemporal resolution, like CORDEX will allow a wider and more accurate view on the possible future outcomes. Finally, the introduction of stochastic programming techniques will allow the selection of an energy hub among the different designs under climate change that can perform optimally for all the possible climate change scenarios.

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