Key features of climate-neutral energy systems for municipalities in different climate zones

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Abstract. The conditions for cities to supply themselves with climate-neutral energy sources vary greatly around the world and depend on many parameters such as the climate, settlement density, intensity of land use, geographical conditions and the economic development stage of the country. Climate-neutral energy system solutions for 7 cities and counties in Europe, Asia and Africa were calculated and compared to identify climate zone-depending patterns for the structures of climate-neutral energy systems. It could be demonstrated that climate zones have a strong influence on the design of climate-neutral energy supply systems, both in terms of renewable energy provision (e.g. solar radiation) and energy consumption (e.g. space heating demand).

1. Introduction
The Paris Agreement as legally binding international treaty on climate change set the goal to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. To achieve this long-term temperature goal, countries aim to achieve a climate neutral world by the middle of this century [1]. More and more cities, as major energy consumers, are actively tackling climate change, setting renewable energy targets and striving for a climate-neutral energy supply in order to make their contribution to climate protection [2].

Climate neutrality of cities means that they cover their energy demands with climate-neutral energy sources; where the renewable energy sources are obtained is usually not specified. The possibility of energy imports, which are usually necessary to achieve the goal, can undermine the incentive for implementing efficient energy systems, which is why it is proposed that cities have to fulfil the following additional requirements to be classified as climate neutral:

1. High energy efficiency in the generation, distribution, storage and consumption of energy.
2. Maximum use of local climate-neutral energy sources, especially solar energy.
3. Energy import is limited to climate-neutral sources, preferably from surrounding rural regions.
4. Smart energy systems with sector coupling, storage, smart control, demand side management, new business models, etc. for secure and cost-effective energy supply are implemented.

Even though the specific energy system of each city is individual, there are universal patterns that follow from general framework conditions. For example, solar and wind energy are the renewable energy sources with the greatest potential in the vast majority of countries [3]. Thus, they will also be the main source of energy in most cities in the future. But while solar energy utilisation mostly takes place within the city boundaries, wind energy must usually be obtained in rural regions around the city.
Furthermore, a strong electrification of the energy system is to be expected, as this is the only way to replace fossil fuels in the heat and the mobility sector by solar and wind energy. Although non-electric heat supplies with biomass, geothermal and solar thermal as well as mobility based on green fuels are expected to be relevant sources of the future energy mix, electricity from renewable energy sources will become the main energy source in the heat and mobility sectors in the future [5].

The transformation of urban energy systems worldwide would be supported if there were better knowledge of climate zone-dependent patterns for the energy system design of climate-neutral cities, as this would allow policy frameworks conditions to be set in a more targeted manner. Furthermore, the knowledge could also contribute to increasing the quality of the conception and planning of urban energy systems. However, studies on climate zone dependency have so far been limited to individual parameters, such as solar radiation [6] or energy demand [7], and are not known for the entire energy system. Thus, there is a need to identify basic patterns of municipal energy systems and, based on this, to investigate to what extent the energy systems are influenced by the climate zones. To determine the extent to which there is a climate zone dependency of urban energy systems, climate-neutral energy concepts for seven cities from different climate zones were calculated and analysed.

2. Energy system optimisation method used

Climate-neutral energy systems differ from city to city, as both energy demands and local and regional renewable energy resources can vary significantly. For the design and planning of climate-neutral energy systems, the planning tools have to account for the fluctuations in generation and dynamics of the system, as well as sector coupling while optimizing complex energy systems with regard to their design and operation. Fraunhofer ISE has developed the “KomMod” energy system model to optimize energy systems at the city/district level and it has been applying this model in national and international projects since 2013. KomMod identifies the cost minimal combination of supply, conversion and storage technologies for an energy system for given specific targets and boundary conditions. The dynamics of the system are taken into account by optimising the entire energy system (electricity, heating and fuel usage e.g. for transport) over one year in hourly temporal resolution. This approach enables the detailed representation of fluctuating energy sources and the in-depth analysis and consideration of the feasibility of each technology [8].

For the input data, KomMod requires demand profiles for electricity and heat in hourly resolution for one year. Furthermore, economic and technological parameters for all considered technologies are required as well as detailed information on the potentials of the available energy sources. Climate data are needed as time series in hourly resolution. For consistency, all data have to be projected for the target year for which the target energy system is to be optimised. Consecutively, the model optimises the supply side of the energy system to achieve the minimal total costs of the energy system while adhering to the given constraints, such as the target share of renewable energy generation or the restriction on energy import or export.

3. Basic data of the city examples

For this study, the energy system solutions for climate-neutral energy supply of 7 cities (and counties) in Europe, Asia and Africa were compared. The calculations were carried out as part of projects with the individual cities. The selected cities are located between the 50th north latitude and the equator. The most northern cities are located in Central Europe, namely, the city of Frankfurt am Main, which is one of the larger cities in Germany with a population of around 0.8 million, and the country of Luxembourg, which mainly consists of the capital city of Luxembourg and has a population of around 0.6 million. Ulaanbaatar, the capital of Mongolia in the Central Asian plains, has a population of around 1.4 million.

In South Korea, the energy system was optimised for the small town of Naju with around 0.1 million inhabitants, and in China for the Xiuzhou district of the city of Jiaxing in Zhejiang province with around 0.6 million inhabitants. Finally, the list is completed with two examples near the equator including the Thai province of Nakhon Pathom with about 0.9 million inhabitants and Kisumu County in Kenya with about 1.2 million inhabitants.
In terms of geographical extent and population density, the practical examples differ greatly. The city of Frankfurt has the highest population density with 3073 inhabitants per km², followed by the city of Xiuzhou with 1073 inhabitants. The other examples range between 171 and 625 inhabitants per km². The large variation in population density is due to the fact that some of the examples are counties, provinces or countries and not just purely urban areas. Also, the administrative definition of municipality is used differently in different countries, e.g. in China the city of Xiuzhou also includes the surrounding rural areas with their villages. The geographical extent is smallest in the densely built-up city of Frankfurt with 248 km². Ulaanbaatar also has a densely built-up centre but it is surrounded by an extensive hinterland that covers 4704 km². In terms of population density, it is comparable to Luxembourg, which is about half of its size (see also Figure 1).

4. Dependence of energy requirements on climate zones
The 7 examples can be assigned to the physical climate zones, specifically the temperate zone (40° - 60°N, Frankfurt, Luxembourg, Ulaanbaatar), the subtropical zone (23.5° - 40°N, Naju, Xiuzhou) and the tropical zone (0° - 23.5°N, Nakhon Pathom, Kisumu County). The physical climate zones, which only take latitude into account, are a good classification in respect of energy supply with solar and wind energy. The energy demand, especially for space heating and cooling, on the other hand, requires a different classification that also takes into account the local temperature profile. The Köppen classification is usually used for this purpose [9]. In this case, the 7 examples would be assigned to 5 climate zones since the temperate zone would be divided into cold semi-arid and oceanic climate zones and the tropical zone into rainforest and savanna climate zones for the related cities. Figure 2 shows the monthly heating degree days (left) and cooling degree days (right) over the course of the year for the 7 cases. Space heating is required mainly in the temperate zone (blue/purple), although it can also get very cold in winter in the subtropical zone (green). In the tropical zone (yellow/orange), there is no space heating demand. In terms of cooling demand, the zones differ significantly. The tropical zone has a year-round cooling demand, which is highest in Thailand from March to May (yellow), while in Kisumu County the highest cooling demand is in January to March (orange). In the temperate zone, there is a relatively low cooling demand in summer (blue/purple). The very large seasonal fluctuation in cooling demand in the subtropical zone (green) is remarkable and in some cases, the monthly values are even higher than those of the tropical zone. The large heating demand in Ulaanbaatar is striking, which is due
to the fact that the city is located in the highlands of Central Asia at an altitude of 1,328 m above sea level and has a strongly continental climate. Kisumu County is located on the equator, but because it is in the highlands of Kenya at 1,157 m above sea level, its cooling demand is much lower than Nakhon Pathom in Thailand.

Figure 2: Monthly heating degree days and cooling degree days over the year for the 7 cases [10]

The energy demands of the cases also differ due to the degree of industrialisation and the level of development of the respective country. Figure 3 shows that the estimated electricity demand in the base year varies substantially between 0.17 MWh per capita and year in Kisumu County and 10.19 MWh in Luxembourg (blue bars). For comparison, the country's specific electricity demand is also shown (grey bars). While efficiency improvements can be expected by the target year, the future development of the economy and the population must be taken into account as well in the design of climate-neutral energy systems. In Europe, changes in the socio-economic factors are relatively small, but in Asia in particular, large growth is expected. An increase in electricity demand is expected in Naju, Nakhon Pathom and especially Kisumu County. Nonetheless, the current large differences between the cases will be far from being compensated by the target year.

Figure 3: Specific electricity and heat demand in base year and in target year for the 7 cases
Significant reduction of space heating demand is expected in the temperate zone (Frankfurt, Luxembourg, Ulaanbaatar) due to improved building efficiencies (see Figure 3, red bars). In the tropical and subtropical zone, heat is needed for domestic hot water and process heat in industry, which is expected to increase with growth in population and economy (Naju, Xiuzhou, Nakhon Pathom). The heat demand in Frankfurt and Luxembourg is about 75% higher than the electricity demand today but it will be about the same in the target year. In Ulaanbaatar, today’s heat demand is nine times higher than the electricity demand and for the target year, a reduction to four times is expected. The cooling demand is not shown separately as cooling is almost exclusively supplied by electricity, which is already included in the electricity demand.

5. Comparison of the climate-neutral energy solutions of the examples

The decisive factor for achieving a climate-neutral energy supply is the sufficient availability of renewable energy sources. Hence, the renewable energy potentials within the city territory must be surveyed. In built-up areas, the potentials primarily consist of solar energy, in rural areas solar is complemented by bioenergy and - at a sufficient distance from built-up areas - also by wind energy. The potential of geothermal and hydropower depends on the topological and geological conditions. Depending on the objectives for climate neutrality, wind, biomass and hydropower potentials from rural areas in the surrounding region are also partially allocated to the city. This allocation enables cost-effective, climate-neutral energy supply, since e.g. the lack of solar energy during winter can be balanced by other renewable sources. In all projects, the renewable energy potential within the city/county boundaries is identified through a detailed analysis and supplemented by the regional potential.

Beside the renewable energy potentials, the electricity, heating and cooling demand for the target year has been projected and the techno-economic parameters of the energy technologies, in particular their costs and efficiencies, have been determined. On this basis, the cost-optimal climate-neutral energy systems for the cities/counties have been calculated, accounting for further framework conditions for different scenarios. In Frankfurt, the goal was climate neutrality with the highest possible share of renewable energies sourced from the city or region [11]. The calculations showed that a complete supply of renewable energy would be possible if wind and bioenergy were also sourced from the state of Hesse. However, a large battery storage capacity would still be needed. Therefore, an energy system was proposed in which 90% of the electricity demand is generated in Frankfurt and the region and 10% is taken from the national electricity grid. The share of self-generated heat supply is 100% in Frankfurt as well as in all other examples.

In Luxembourg, a self-sufficiency rate of 70% was chosen for electricity generation due to costs, as significant electricity storage capacities would have to be installed for higher rates. In Ulaanbaatar, the goal was to achieve complete self-sufficiency with renewable energies, since abundant solar and wind energy potentials are available. However, due to a low solar yield during the cold winters accompanied by low wind energy yields during longer winter periods, complete self-supply would imply the installation of very large electrical and thermal storage facilities. Due to economic considerations, an electricity self-sufficiency rate of 86% has been proposed. In Naju, despite the almost complete use of solar and wind potential, only 35% electricity self-sufficiency is achieved. In Xiuzhou, the solar and wind potential is very limited as well due to the dense development and the agricultural use of the open spaces, combined with high energy consumption by industry. Therefore, the electricity self-consumption is only 37%. In Nakhon Pathom and Kisumu County, the solar potential is very high and is available all year round due to the proximity to the equator. At the same time the electricity demand is comparatively low, complete self-sufficiency is achieved by installing electrical storage units buffering the daily solar energy production cycles. Figure 4 shows the optimized energy mix for electricity and heating supply for the seven cases.

The comparison shows that for the temperate climate zones, an almost equal share of solar and wind in the energy mix (Frankfurt, Luxembourg, Ulaanbaatar) is the optimal solution. However, in most cases, the usable wind potential is the limiting factor. In many cases, wind and solar energy generation complement each other very well, as wind energy generation is higher in winter than in summer.
However, this is not the case in the cold semi-arid climate of the Central Asian highlands for the example of Ulaanbaatar. In Naju and Xiuzhou, located in the subtropical zone, there is also little or no wind potential and the solar potential is limited as well since the existing land areas are densely built-up. Thus, only relatively low self-supply rates are possible here. Cities of this type have to be supplied with imported climate-neutral generated electricity. It can be concluded that there is sufficient solar potential available for year-round supply in tropical regions, which can cover most of the electricity demand if electrical daytime storages are installed. However, in case biomass or waste resources are sufficiently available for electricity generation, they are more likely to be used as long as they are cheaper than the combination of PV system and battery storage.

Figure 4 Shares of the different energy sources for covering the electricity demand (left) and the heat demand (right) for the 7 cases

6. Conclusions
The study results demonstrate the strong dependency of the energy mix of climate-neutral energy systems for cities on their climate zones. Solar energy is the basic energy source in all cities with a share of electricity supply mostly between 25% and 78%. In Naju, its share is only 11%, but here the import share is also very high at 65%. Wind energy is a key source of electricity as well, with a share of between 31% and 44% of electricity demand, but only in the temperate climate zone. In the tropical or subtropical zone, there is often only little or no wind potential. Bioenergy and energy from waste incineration are complementary renewable energy sources, but their potential depends mainly on local conditions and not on the climate zone. If bioenergy and energy from waste incineration are available, they can play an important role in heat supply; where they are not, heat supply with electricity dominates above all. Solar thermal energy can make contributions of up to about 22% to the heat supply in the seven cases, but it is only used in three of them.

In temperate and cold climate zones, an energy supply mainly based on solar energy is not possible due to the low amount of irradiation during winter, when the space heating demand is high. A similar percentage of electricity generated by solar and wind can be typically observed here. Moreover, the potentials for energy generation from biomass and waste are fully utilised, but these technologies only have a subordinate share in the energy mix usually. Furthermore, complete self-sufficiency with local renewable energy sources complemented by wind and bioenergy from the surrounding region would only be possible with very large storage capacities. Hence, an electricity import rate of 10% to 30% from the national grid has been proposed in the temperate zone cases presented.

In the subtropical examples, the potential for renewable energy, including solar energy, is very limited. Thus, over 60% of the electricity demand must be imported. Presumably this is caused by the location in the densely built-up and intensively used regions of Southeast Asia rather than the climate zone, but more examples would have to be studied to assess this. In the tropical zone, a complete energy supply by local and regional renewable energy is possible, with solar energy taking the dominant role due to its low cost and year-round availability. Energy from biomass and waste can serve as a stabiliser for the fluctuating solar energy supply and is preferred to the combination of solar energy and electrical...
storage as long as it is available and at lower total costs. In Kisumu County, solar energy can provide 50% of the electricity supply since the energy demand is very low.

The following general findings can be derived from the presented results:

- The energy mix of climate-neutral energy systems of cities depends decisively on the climate zone due to a high dependency of the space heating and cooling demands on the climatic conditions and the dependency of solar energy availability during the year on the latitude. However, the energy system is additionally strongly influenced by the energy demand density and the local availability of wind, biomass and energy from waste.

- A high rate of self-supply with solar energy is possible in tropical zones, in subtropical and temperate zones it must be complemented by wind and bioenergy from the surrounding region.

- The coupling of the electricity, heating, cooling and mobility sectors has to be considered as a key characteristic for the design of climate-neutral energy systems, since climate-neutral heat supply and mobility provision is only possible through partial electrification.

It should be noted that the examples presented do not cover all climate zones and the local framework conditions of the cities. Furthermore, in addition to the climate zones also the availability of biomass and the energy demand density influence the design of the climate-neutral energy system. Nevertheless, the dependence of energy system structures on climate zones could be clearly confirmed by the studied cases. Consequently, it is recommended to consider the climate zones in an even more differentiated way in further studies, to categorise the energy system patterns even more strongly and to concretise and quantify the dependence of the energy system design on the climate zone.

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