The impact of limited electricity connection capacity on energy transitions in cities

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(article starts on next page)

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The impact of limited electricity connection capacity on energy transitions in cities

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ABSTRACT

We study the impacts of the connection capacity for electricity transfer between a city and a regional energy system on the design and operation of both systems. The city energy system is represented by the aggregate energy demand of three cities in southern Sweden, and the regional energy system is represented by Swedish electricity price area SE3. We minimize the investment and running costs in the electricity and district heating sectors, considering different levels of connection capacity between the city and the regional energy systems; connection capacities equal to 100%, 75%, 50% and 0% of the maximum city electricity demand. We find that a system design with 50% connection capacity is only 3% more expensive in terms of total costs than a system with 100% connection capacity. However, shifting electricity generation capacity from the regional to the city energy system with 50%, as compared to 100%, connection capacity leads to a higher marginal cost for electricity in the city than in the region. With the highest connection capacities, 75% and 100%, the district heating sector in the city can support wind power integration in the regional energy system by means of power-to-heat operation. Modeling systems with different connection capacities makes our results applicable to other fast-growing cities with potential to increase local electricity production and sector coupling between the electricity, district heating and electrified transport sectors.

1. Introduction

Strategies for a timely energy transition are being developed on different political and geographic levels. Energy targets are set by urban and municipal stakeholders and are part of national and European plans. In recent years plans and ambitions for climate change mitigation have been formulated in a multitude of cities in the EU and Sweden. Those plans often involve targets for emission reductions and for renewable energy generation on the city scale [1,2]. The scalability of technologies such as solar photovoltaic (PV) allows for the installation and integration of these technologies in the urban environment. The large-scale renewable electricity generation in locations that are most favorable for wind and solar power, on the other hand, requires the transmission of electricity to urban area and, thus, a strong grid infrastructure that can balance fluctuations over a larger geographic area [3]. To which extent local, small-scale and large-scale, more-centralized energy solutions will coexist and be combined in a future fully decarbonized energy system is not yet clear.

The utilization of synergies between different energy system sectors is seen as an important element for an efficient decarbonization of the system. Electrification and the use of electricity as a cross-sectoral energy carrier increases the potentials for synergies and thus, for sector coupling. Energy systems with a focus on the integration of different sectors, such as electricity, heating and cooling, the built environment and the transport sector, and on the utilization of system flexibilities derived from sector coupling and from the use of storage systems, are generally referred to as *smart energy systems* [4–6].

In city energy systems the physical proximity of energy demands for e.g., electricity, district heating and to fulfill transport demands, provides favorable conditions for sector coupling. District heating systems have been found to offer potentials for system flexibility and synergies to other sectors through: use of power-to-heat (PtH) technologies such as heat pumps [7] and flexible operation of combined heat and power (CHP) units [8,9], together with the usage of thermal energy storage (TES) systems [10,11]. In the transport sector, flexible charging strategies for battery electric vehicles (BEVs) can facilitate synergies to the electricity sector, aid

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the uptake of local renewable electricity generation [12] and increase the self-consumption of renewable electricity generation [13,14]. Cities with a focus on developments that efficiently integrate sectors, infrastructures, resources and actors, while simultaneously aiming to improve climate, environmental, societal and economic performances are frequently referred to as *smart cities* [15–17]. Smart city developments are often facilitated by the use of information and communication technologies. The sustainability of cities can be assessed for different aspects covering urban energy, water and environment systems. A recent study benchmarking 120 cities has shown that future scenarios including cross-sectoral strategies and the use of residual energy can improve city sustainability indicators [18].

Cities and urban areas continue to expand rapidly and are estimated to accommodate about two-thirds of the global population by the middle of the century [19]. As a consequence of fast city growth several cities have identified an immediate or imminent need for power grid expansions, or more specifically, to increase the connection capacity to the surrounding regional energy system [20,21]. This need is intensified by the ongoing electrification in different sectors of the energy system. A larger connection capacity to the regional system enables larger hourly import of electricity to the city. Bottlenecks in the electricity exchange between the city and the regional system risk to decelerate city development projects or hamper further measures towards the energy transition. Grid infrastructure expansion projects are often associated with long lead-times. An alternative or complementary strategy to grid expansion are the increased local generation of electricity and the utilization of system flexibility and synergies between energy system sectors.

The planning and operation of city energy systems influence and are influenced by the surrounding energy system. Moreover, strategies for the energy transition should be aligned between the city, municipal and national levels [22]. However, many analyses of the decarbonization of city energy systems or the installation and operation of local energy technologies [23–26] are performed on isolated systems or with a simplistic representation of the connection to the surrounding system. Few modeling studies in literature consider both, small-scale and larger-scale energy systems [27–29]. Thellufsen and Lund [27] have proposed a methodology to quantify the levels of integration between local and national energy systems. In a case study of two Danish cities, Thellufsen and Lund have used the need for the exchange of excess electricity generation between local and national systems as an indicator of how well-integrated the systems are, whereby a distinction is made between integrable excess electricity, which can be handled between the two systems, and non-integrable excess electricity that requires other measures, such as a change in production profiles or the export to other energy systems. Pilpola et al. [28] and Arabzadeh et al. [29] have studied the impacts of different system limitations and available technologies in city and national energy systems and have directly compared decarbonization scenarios for both systems using two different models. However, none of the aforementioned studies [27–29] included a dynamic interaction in the form of electricity exchange between the small-scale and larger-scale systems in the modeling, as is done in the present work.

The aim of this work is to study the impacts of limitations to the electricity connection capacities between cities and the surrounding regional energy systems (in this paper denoted as the city-scale and regional-scale energy systems, respectively[1]) on the design and operation of both systems. For this purpose, we model an aggregate of three cities in southern Sweden (the city scale) and the electricity spot market price area in which they are located (the regional scale), and compare four different levels of connection capacity, i.e., the capacity that limits electricity exchange between the two systems. The three cities considered in this work have identified bottlenecks in the grid infrastructure used to import electricity from the surrounding electricity system as a possible barrier to further city growth, including the establishment of new industries [20]. This work supplements previous studies in linking the modeling of the city and regional energy systems and analyzing not only the operation, but also the cost-optimal design of decarbonized energy systems on both scales. The modeling setup allows investigations of the roles of electricity connection capacities, in combination with the utilization of flexibility from sectoral coupling in the city and regional energy systems.

The remainder of the article is structured as follows: First, the model description, the modeling cases and input data are introduced. Then, results on the system designs and operations, and on the costs of the different modeling cases are shown. Finally, a discussion of the findings and the conclusions of the work are presented.

2. Methodology and data

We apply two modeling tools that, for the purposes of this study, have been refined and combined into a single model. The combined model is a linear optimization model that minimizes the total costs for investment, operation, and power plant cycling with a 3-h resolution over 1 year and considers the city-scale and regional-scale energy systems as separate nodes, between which electricity exchange is possible. The modeling of the city energy system is based on a city energy system optimization model presented previously by Heinisch et al. [30], which was subsequently developed further [31] to include different charging strategies for electric vehicles (EVs), more specifically battery electric private cars and public buses. The regional energy system is based on the ENODE model, which was introduced by Göransson et al. [32] and expanded by Taljegård et al. [33] to include battery electric cars and by Holmér et al. [10] to include a representation of the district heating sector. We integrate the equation structure of the two models and consider the data for the city electricity and heating profiles and for the resource availability for the regional electricity supply, sourced from the original models.

Fig. 1 shows an overview of the modeling of the two scales, i.e., the two nodes in the modeling. The optimization yields the cost-effective investments and operation for the city and regional energy systems, considering electricity exchange between them, which is limited by the connection capacity. While both scales include the electricity and district heating sectors and electrified private cars, some technologies for electricity generation are assumed to be available only in the regional system (i.e., wind, hydro and nuclear power). In addition, industrial excess heat to cover parts of the heat demand is assumed to be available only in the city node. We apply a Greenfield approach, i.e., no existing capacity in either modeling node is considered, with the exemption of hydropower in the regional system (see Section 2.2 for details). The Greenfield modeling yields results on the cost-optimal system designs for the modeled year and the different modeling cases, rather than transition pathways from today's system.

[1] The regional energy system is in turn surrounded by other regions, i.e., prices areas, which are often defined by limitations in transmission capacity (some countries have only one price area for the entire country in spite of regional limitations in transmission capacity), which however are not part of the modeling in this work.

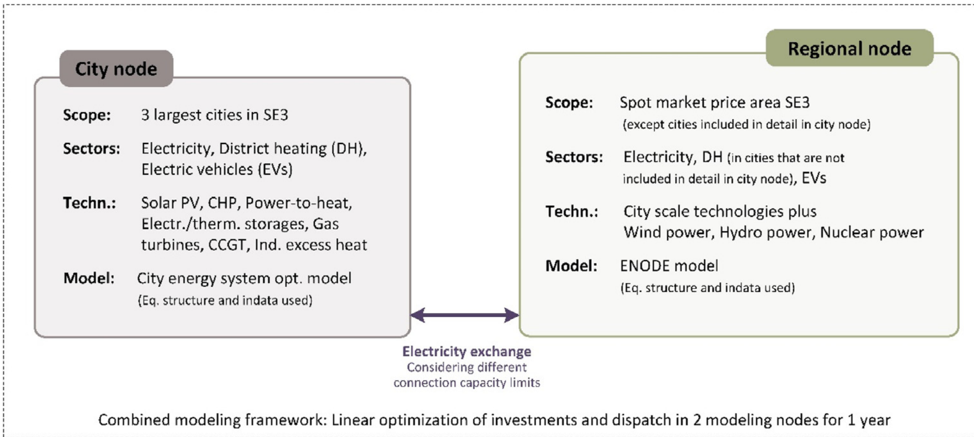

Fig. 1. Schematic of the model, including details of the scope, sectors and technologies considered in the city and regional energy systems. The two original models for the two systems have been combined into a single model for this work.

2.1. Model formulation

The City and the ENODE models use a similar equation structure, including a cost-minimizing objective function, energy balances on electricity and heat, and additional technical constraints, which are combined in this work. This section describes the objective function, electricity and heat balances, and constraints on the electricity exchange. The remainder of the model description is in the *Supplementary material*. A variable is introduced to represent the electricity exchange between the city and the regional scales. Thus, the objective functions can be written as:

$$MIN: \; C^{tot} = \sum_{i\in I}\sum_{r\in R}\left(\left(C_i^{inv}+C_i^{OMfix}\right)s_{i,r}+\sum_{t\in T}\left(C_i^{run}\left(p_{i,r,t}+q_{i,r,t}\right)+\sum_{r2\in R\backslash r}\left(x_{r,r2,t}C^{tr}\right)\right)\right) \tag{1}$$

where I is the set of all technologies, T is the set of time-steps and R is the set of the two modeling nodes, the city- and the regional-scale node. The investment costs, the fixed operational and maintenance costs and the variable running costs per technology i, are denoted C_i^{inv}, C_i^{OMfix} and C_i^{run}, respectively. The variable $s_{i,r}$ is the capacity per technology i that is installed in each node r, and $p_{i,r,t}$ and $q_{i,r,t}$ are the electricity and the heating generations per time-step t and node (city or regional) r, respectively. For the electricity exchange $x_{r,r2,t}$ between the two nodes r and $r2$ and per time-step t, the costs C^{tr} are considered.

The electricity balance that matches supply and demand while considering electricity exchange between the two nodes is written as:

$$D_{r,t}^{el}+b_{r,t}^{ch}-b_{r,t}^{dch}+\sum_{i\in I_{PtH}}\frac{q_{i,r,t}}{\eta_i}+EV_{r,t}^{ch}-EV_{r,t}^{V2G}+\sum_{r2\in R\backslash r}x_{r,r2,t} \le \sum_{i\in I_{el}}p_{i,r,t}\;,\;\forall\, t\in T,\; r\in R \tag{2}$$

where I_{PtH} is the subset of set I for all power-to-heat (PtH) technologies and I_{El} is that subset of I for all electricity generation technologies, not including battery systems. The demand for electricity, $D_{r,t}^{el}$, is given per node r and time-step t, the electricity generation $p_{i,r,t}$ per technology i, node r and time-step t, and $x_{r,r2,t}$ is the electricity exchange from r to $r2$ per time-step t. The heat production from PtH technologies $q_{i,r,t}$ is included here to represent the power consumption for PtH per technology i, node r and time-step t, including η_i, which gives the coefficient of performance (COP) for heat pump technologies and the efficiency of electric boilers. The charging and discharging of stationary and electric car batteries per node r and time-step t are written as $b_{r,t}^{ch}$, $b_{r,t}^{dch}$, $EV_{r,t}^{ch}$ and $EV_{r,t}^{V2G}$, respectively. Charging and discharging (V2G for car batteries) is subject to additional constraints, which for electric cars include the requirement to meet the car driving demand at each time-step.

The heat balance to match the demand and supply of heat in both nodes is given by Eq. (3). No exchange of heat is considered between the city and the regional nodes.

$$D_{r,t}^{h}+\sum_{i\in I_{TES}}\left(h_{i,r,\,t}^{ch}-h_{i,r,\,t}^{dch}\right)\le\sum_{i\in I_H}q_{i,r,t}+Q_{r,t},\;\forall\; t\in T,\; r\in R,\;\{r2=R\backslash r\} \tag{3}$$

where I_{TES} is the subset of thermal storage technologies, i.e., tank and pit storages, and I_H is the subset of all heat generation technologies, including PtH technologies. The district heating demand per node r and time-step t is written as $D_{r,t}^{h}$, and $q_{i,r,t}$ is the heat generation per technology i, node r and time-step t. The thermal storage charging and discharging per TES technology i, node r and time-step t are written as $h_{i,r,\,t}^{ch}$ and $h_{i,r,\,t}^{dch}$, respectively, and $Q_{r,t}$ is the industrial excess heat per node r and time-step t, which is assumed to be zero in the regional node, that represents both small towns without substantial excess heat used for district heating and rural areas.

The connection capacity that is available between the city and the regional nodes limits the electricity exchange between them, as given in Eq. (4). The electricity export from the regional node has to be equal to the electricity import to the city node, and vice versa, as given in Eq. (5).

$$x_{r,r2,t} \le Z,\ \forall\ t \in T,\ r \in R,\ \{r2 = R \backslash r\} \tag{4}$$

$$x_{r,r2,t} = -x_{r2,r,t},\ \forall\ t \in T,\ r \in R,\ \{r2 = R \backslash r\} \tag{5}$$

where $x_{r,r2,t}$ is the electricity exchange from r to $r2$ per time-step t and Z is the connection capacity limit between the city and regional nodes. Additional equations for the energy balances over storage systems, EVs and constraints on generation are listed in the *Supplementary material*.

We analyze the local marginal costs of electricity and heat in the city and regional nodes, which are the marginal values of the electricity and heat balances in Eqs. (2) and (3) at each hour. The marginal values are a measure of the costs to supply one more unit of electricity or heat to the city and regional energy systems. Thus, the local marginal costs are good indications of the costs to supply the electricity and heating demands at each hour. In hours in which bottlenecks in the grid infrastructure occur, i.e., the connection capacity for electricity exchange is fully utilized, the marginal costs in the city and regional energy systems typically differ.

2.2. Modeling cases

Table 1 provides a summary of all the modeled cases. The main focus of the modeling work are the four levels of connection capacity between the city and regional nodes, studied through the four *Base* cases. With 100% connection capacity, the maximum existing electricity demand per hour on the city scale can be fully supplied by electricity imported to the city from the regional system. The existing demand is from current electricity consumers in the city energy systems and, thus, does not include the new electricity demands from electrified transport or PtH technologies that are considered in the model. Correspondingly, 75% and 50% connection capacities meet 75% and 50% of the maximum city-scale demand hours, respectively, while the 0% connection capacity does not allow electricity exchange between the city and regional energy systems.

In addition to the *Base* cases, we investigate the role of the flexibility obtained through the flexible dispatch of hydropower, the flexible charging of electric private cars (here denoted as EVs), and from coupling to the district heating sector in a set of extra cases (*NoHydro, EVFlex, NoTES*), all considering the four different levels of connection capacity. The *NoHydro* cases are used to study a hypothetical system without access to hydropower, in order to assess the impact that the large amount of hydropower in the Swedish system has on the results (hydropower is modeled within the SE3 region and as import into SE3 from northern Sweden). In the *EVFlex* cases, the Smart charging of electric passenger cars is considered, i.e., charging that can be postponed to a later time under the condition that all the driving demand is met. Electric car charging is also included in the *Base* cases. However, in contrast to the *EVFlex* cases, in the *Base* cases EVs are modeled with a fixed demand profile, i.e., the cars are charged directly when parked and no flexibility is available from the electric transport sector. The *EVFlex* cases also allow for vehicle-to-grid (V2G) discharge, i.e., electricity can be discharged from the vehicle batteries to the electricity system. The *NoTES* cases exclude the flexibility provided by the use of thermal storage systems in combination with PtH technologies. All the modeling cases assume electrification of 60% of today's registered cars and include a requirement for zero emissions from electricity and heat generation. The remainder of the private car fleet can be assumed to run on renewable fuels such as biofuels, which are outside the scope of this paper.

2.3. Input data and representation of the city and regional scales

The model is applied to a spot market region in Sweden and the three largest cities in the same region, thus:

- The city scale represents an aggregate of the three cities Stockholm, Gothenburg and Uppsala. The aggregation involves summarizing the electricity and heating demands and the number of registered cars in the three cities.
- The regional scale represents the spot market price area SE3 in southern Sweden, which the three cities are located in. The demands for electricity, heating, and private transport that are modeled on the city scale are excluded from the total demands on the regional scale. Thus, the regional energy system represents the remaining cites (with <200,000 inhabitants), towns and rural areas and the centralized electricity generation that is installed outside of the three largest cities.

Results are presented for the SE3 region and the aggregate of the three cities.

The three cities that are studied have identified current or future challenges associated with bottlenecks in the infrastructure to exchange electricity with the regional system. All three cities are growing and expanding. Additionally, a trend towards electrification inside the cities is ongoing, while local electricity generation from CHP units is decreasing [34–36]. For the city of Stockholm we consider the metropolitan area to be represented on the city scale of the modeling. The reason is that in Stockholm bottlenecks in the grid infrastructure have been identified towards the high-voltage

Table 1
Overview and descriptions of the modeling cases.

Case	Modeling assumptions	Connection capacities considered[a]
Base	Electricity and district heating on both scales; 60% private car electrification with a fixed charging profile; Zero emissions from electricity and heat generation	
NoHydro	Base cases without hydropower capacity on regional scale	0%, 50%, 75% and 100% of the maximum
EVFlex	Base cases with flexible EVs instead of fixed charging profile, i.e., Smart charging and vehicle-to-grid (V2G) discharge is possible for the private car fleet	city-scale load[b]
NoTES	Base cases without thermal storage systems on either scale, i.e., yielding less coupling between electricity and the DH sector	

EV, electric vehicle; DH, district heating.

[a] Connection capacity is the capacity that limits electricity exchange between the city and the regional node in the modeling.

[b] Existing electricity demand on the city scale, not including new loads from the electrification of electric vehicles and power-to-heat technologies that are included in the modeling.

transmission grid [34]. For the cities of Gothenburg and Uppsala we consider the geographical area that the city distribution grid covers to be represented on the city scale in the modeling. The *Supplementary material* provides further information on which municipalities and counties are considered for the city and regional nodes in the modeling.

We model a future system (Year 2045) with a requirement for zero emissions from electricity and heat generation. In the national Swedish system net zero emissions are to be achieved by Year 2045 [37]. In the three cities that this work focuses on, more specific targets have been formulated: Gothenburg aims for a renewable electricity and heat generation by 2025 [38], Stockholm aims to be fossil-free and climate-positive by 2040 [39] and the goal in Uppsala is a municipality that is fossil fuel-free by 2030 and climate positive by 2050 [40]. As we model a city-scale and a regional-scale energy system, we have chosen to apply the same zero emission targets in both, which, thus, represents Year 2045, even though the three cities have expressed more ambitious targets.

This study utilizes current demand profiles for electricity and heat and, thus, makes no assumptions on demand growth in the city energy systems due to urbanization, or concerning the impacts on the demand profiles from increased energy efficiency. Instead, the focus in the modeling is on investigating different levels of connection capacities to the city energy system and prognoses of future changes in population and energy efficiency efforts are outside the scope of this work. The cases reflect situations, in which electricity demand on city scale is larger than the connection capacity. These assumptions, thus, include the challenges of limited connection capacity into fast-growing cities. The modeling, however, does not consider any changes to the share of the total population that lives in the three largest cities and to the corresponding energy demand. It is not unlikely that urbanization in the upcoming decades affects these largest cities more than other, smaller cities. To represent the differences in the magnitudes of the demands for electricity, heat and transport in the city and regional nodes, we use statistical data for the annual electricity and district heating demands [41] and for the number of registered cars [42] of different Swedish municipalities in Year 2019. The data is obtained for per Swedish municipality; details on the categorization of municipalities into the city and regional nodes are found in the *Supplementary material*. For the hourly demand profiles, we utilize real data acquired for the electricity demands in Gothenburg and Stockholm. For Uppsala, even though no hourly data are available, the total annual demand is known. Thus, we use the two profiles from Gothenburg and Stockholm, which are scaled to fit the annual electricity demand of Uppsala to represent this city. For the regional node, we use the electricity demand profile for the SE3 price area from the original ENODE model (which, in turn, is based on electricity demand data from ENTSOE for Year 2012). This demand is scaled according to the statistical data for the annual electricity demands of 2019 in the municipalities that are part of the SE3 region (i.e., excluding the demands of the three cities that are included in the city node). The demand profiles for the city and regional scales exhibit a similar shape. Access to an hourly district heating demand profile was limited to Gothenburg. Therefore, the Gothenburg profile has been used, scaled according to the statistical data for annual district heating demands, for all three cities. In the regional node, the district heating demand represents small-to-medium cities (i.e., less than 200,000 inhabitants) with district heating in the SE3 region that are not part of the city node. Smaller cities are not assumed to experience the same city growth as the larger cities modeled on the city scale. Thus, the challenges associated with bottlenecks in the electricity connections to smaller cities are assumed to be less severe. The hourly electricity and district heating demand profiles in the city and regional energy systems are found in Fig. S1 in the *Supplementary material*.

Fig. 2 summarizes the statistical data used to represent the city and the regional scales in the modeling, as explained above. The regional scale has about 20% more inhabitants than the city scale (about 3.9 million and 3.2 million inhabitants in the regional-scale and the city-scale systems, respectively), and about 40% more registered cars. The electricity demand on the regional scale is clearly larger than the demand on the city scale, which is partly due to a lower per capita use of electricity in densely populated areas and the presence of large electricity consumers such as industries, which are often located outside of city areas. The district heating demand, however, is almost as high for the city scale as for the regional scale, as the largest district heating networks are located in the most densely populated areas. These differences in the relationships between electricity and heating demands, as well as the spatial requirements of large-scale energy technologies suggest different strategies for energy system decarbonization on the city and regional scales, which is the basis for the present work.

Table 2 provides a summary of the technologies considered in the modeling of both scales. Hydropower located in northern Sweden (i.e., price areas SE1 and SE2) is made available to SE3 via high-voltage transmission lines. The hydropower capacity in the model is, therefore, assumed to be equal to the hydropower capacity in SE3 plus the cable capacity from northern Sweden (9.6 GW in total for SE3). An energy limit is set on the possible annual import of hydropower to SE3, corresponding to the inflow in the SE1 and SE2 regions minus the annual demand for electricity in these regions. No investment costs are assumed for this fixed hydropower capacity. The hydropower can be operated flexibly as long as the energy balance, considering the water inflow and hydropower storage limitations, is fulfilled (the equations for hydropower are given in the *Supplementary material*).

Industrial excess heat for district heating is, in the three cities that are investigated in this work, mainly available in the city of Gothenburg, from refineries [44]. As the future availability and utilization of this excess heat are uncertain, we assume a reduction as compared to the currently available excess heat. Thus, the excess heat profile from Gothenburg in 2012 multiplied with the factor 0.7 is utilized for the city-scale system. With this assumption, the industrial excess heat in the city energy system amounts to 14% of the city-scale district heating demand. For the district heating systems included in the regional-scale system, no excess heat has been assumed. The regional scale represents small-to-medium cities, which currently have no significant use of excess heat. However, an increase in industrial excess heat usage in the future is not unlikely. No district cooling infrastructure is considered within the scope of this study.

The EV driving demand is based on the driving patterns derived from a GPS measurement campaign in western Sweden [45,46], which have been converted to the hourly EV driving demand for the modeling in this work, as first presented in Ref. [47]. (Details of the method and assumptions to create the electric car driving demand profiles can be found in the *Supplementary material*).

The assumptions on future investment and operational costs of the different technologies are found in the *Supplementary material*. We do not include costs for the connection capacity, since the connection capacities are part of the case descriptions and, thus, inputs to the model.

3. Results

Below we provide results in terms of design and operation of city and regional energy systems for different connection capacities, as obtained from the modeling in the different cases, and the corresponding implications on costs of these systems.

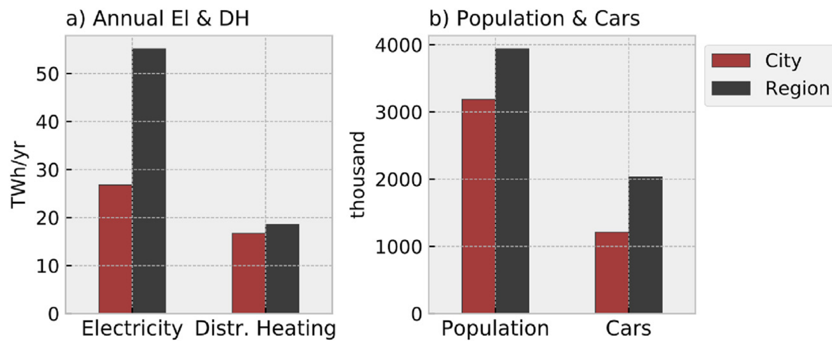

Fig. 2. Scale differences between the city and regional nodes, for annual electricity and district heating demands (a) and population and number of registered cars (b), from the statistical data [41–43] used as input to the modeling.

Table 2
Overview of the electricity generation, heat production, combined heat and power and storage technologies considered in the modeling of the city and regional scales.

	Common to the city and regional scales	City scale only	Regional scale only
Electricity generation	Solar PV; Gas turbines fired by biogas; Combined cycle power plants fired by biogas (CCGT)		Wind power, Hydropower, Nuclear power
Heat production	Heat pumps; Heat-only boilers fired by biofuels or electricity [a]	Industrial excess heat	
Combined heat and power (CHP)	CHP units fired by biomass fuels or waste		
Storage technologies	Li-Ion batteries; Tank storages; Pit storages		

[a] Heat pumps and electric boilers are presented in combined form as power-to-heat (PtH) technologies in the results.

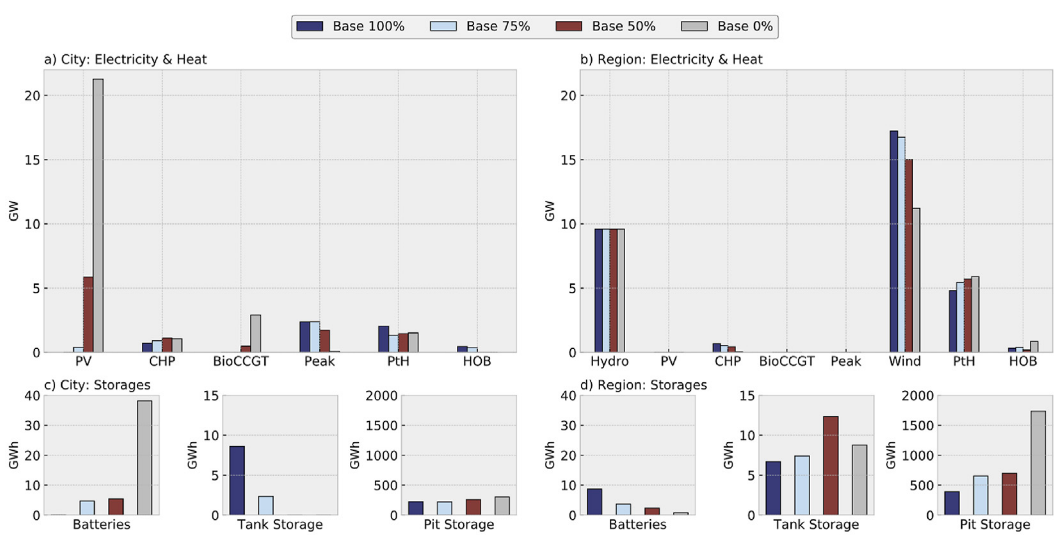

Fig. 3. Capacities for electricity and heat generation in the city-scale (a) and regional-scale (b) energy systems, and storage technologies on the city (c) and regional (d) scales for the four Base cases with connection capacities corresponding to 100%, 75%, 50% and 0% of the maximum city scale load hour, as obtained from the modeling. CHP, combined heat and power plants (for which the electricity generation capacity is plotted); CCGT, combined cycle power plants; Peak, gas turbines used for peak power generation; PtH, power-to-heat technologies, for which the heat generation capacity is plotted; HOB, heat-only-boilers (except electric boilers which are included in PtH).

3.1. System designs and operation

Fig. 3 shows the capacities of the electricity, district heating and storage technologies for the four *Base* cases and for the city and regional scales, as results of the optimization. It is evident that the amount of electricity exchange that is possible between the city and the regional energy systems (defined by the connection capacity in the modeling) influences the optimal system compositions on both scales. With lower connection capacities between the city and the region, the wind generation capacity on the regional scale decreases (Fig. 3b), while the capacities of solar PV, CHP and CCGT plants (Fig. 3a) and battery systems (Fig. 3c) on the city scale increase. The solar PV capacities on the city scale amount to: less than 10% of the maximum demand hour on city scale in the case with 75% connection capacity; about 7% larger than the maximum demand hour with 50% connection capacity; and almost four times the maximum demand hour in the case without electricity exchange between the city and regional energy systems, i.e., 0% connection capacity. While a system without electricity exchange can be expected to require a large capacity for local generation on the city scale, the investments with 50% connection capacity are much more similar to the city system designs with 75% and 100%

connection capacity, than that with 0% connection capacity.

A connection capacity of 100% results in the largest PtH capacity in the city energy system (Fig. 3a), which is operated throughout the year. In this case, the PtH operation on the city scale coincides often with peaks in wind power generation on the regional scale and the consequent peaks in electricity exchange to the city. However, in the cases with PV on the city scale (i.e., mainly with 50% and 0% connection capacities), PtH is operated predominately during summertime in combination with solar PV, while the wintertime heat demand is covered by larger CHP capacities. This is due to the limitation on the connection capacity and the overall higher electricity demand during winter. With 100% connection capacity the largest electricity generation capacity on the city scale is from gas turbines, which serve as peak generation. In the modeling case with 0% connection capacity most of the electricity generation capacity on city scale is solar PV and almost no peak generation units are installed. Pit storages are the dominant storage option in all modeling cases and on both scales (>95% of the total storage volume in all but the case with 0% connection capacity) and are used to cover the winter peaks in the district heating demands. (The *Supplementary material* includes additional figures addressing the hourly dispatch of technologies over a full model year.)

On the regional scale, the decreasing levels of connection capacity, in contrast to the city scale, result in decreasing battery capacities. At the same time investments in PtH and pit storages increase (Fig. 3, b and d). At high connection capacities, electricity exchange to the city scale and batteries are used to manage variations on the regional scale. With a lower connection capacity, the electricity exchange to the city scale is not only lower overall, but is also less-variable (since the maximum capacity is used more frequently). At lower connection capacities, variations at the regional level are instead primarily managed by PtH in combination with thermal storage systems and hydropower. The results show that PtH technologies can be an important measure to balance fluctuations in wind power. Moreover, the availability of this flexibility is highly dependent upon the electricity connection capacity to cities with district heating systems. Since the total wind power capacity is lower at lower levels of connection capacity, the existing hydropower can contribute to variation management to a greater extent.

Fig. 4 shows the results for the capacities of the electricity, district heating and storage technologies for the *NoHydro*, *EVFlex* and *NoTES* cases. The impact of removing the access to flexible hydropower, considering Smart charging rather than fixed charging for electric cars and omitting the use of thermal storage systems, is presented below.

NoHydro (Fig. 4a): The electricity generation and flexibility provided by hydropower are substituted by a combination of technologies on both the regional and city scales. When comparing the *Base* and *NoHydro* cases, i.e., Figs. 3 and 4a, one observes higher levels of wind power on the regional scale (on average for the different connection capacities, 27% higher than in the *Base* case). Yet, compared to the *Base* cases, the results from the *NoHydro* cases also show investments in solar PV, peak power, CCGT, and nuclear plants, and an increase in battery capacities. The investments in battery capacity for the *NoHydro* case are larger than those for the corresponding *Base* case, ranging from 3-fold larger with 100% connection to >30-fold larger without electricity exchange between the city and regional energy systems. The PtH technologies are operated more flexibly to balance fluctuations in wind power generation, and pit storages are, in contrast to the *Base* cases, charged and discharged more frequently throughout the year (for all levels of connection capacity investigated). With 100%, 75% and 50% connection capacities, the electricity exchange between the regional and city scales fluctuates to a greater extent than in the corresponding *Base* cases, with more time-steps of electricity export from the city scale to the regional scale. This is partly due to the missing flexibility from flexible hydropower dispatch on the regional scale and partly because all the connection cases result in investments in solar power on the city scale, and these are larger than in the corresponding *Base* case.

EVFlex (Fig. 4b): With flexible electric car charging and V2G, the utilization of stationary battery systems is, in almost all the modeling cases, replaced by vehicle batteries. This is, obviously, a consequence of the vehicle batteries being made accessible to the electricity system without cost (but still fulfilling the driving demand). Thus, since the vehicle batteries provide a large capacity and storage volume for system (21.8 GWh on the city scale and 36.6 GWh on the regional scale, which are significantly larger than the stationary battery sizes obtained from the optimization in the *Base* cases in Fig. 3, except for the city scale in the *Base* case with 0% connection capacity). The vehicle batteries facilitate the integration of the generation from varying renewables, provided that flexible charging with V2G is implemented. We find that flexible charging and discharging of vehicle batteries stimulate a larger increase in wind power capacity on the regional scale than does an increase in solar PV on the city scale, when comparing with the capacities in the *Base* cases. Solar PV on the city scale is combined with stationary batteries also in the *Base* cases, which is expected and indicates that batteries are valuable in combination with solar PV. Thus, the availability of EV batteries at no cost to the system has a greater impact on the wind power capacity on the regional scale (increase of between 1% and 10% compared to the *Base* cases with different connection capacities) than does the city-scale solar PV (increase compared with the *Base* case only with 50% connection capacity).

NoTES (Fig. 4c): Not allowing for the utilization of thermal storage systems results in higher levels of heat-only boilers on both the city and regional scales (0.5−2.8 GW increase for the different levels of connection capacity) and a reduced capacity for the PtH technologies on the regional scale, which is followed by a reduction in wind power capacity (8%−14% reduction compared to the corresponding *Base* case, for different levels of connection capacity). As there are not thermal storage systems in the *NoTES* modeling cases, battery systems are the only storage systems utilized.

Fig. 5 compares the electricity exchange between the regional and city scales in the *Base*, *NoHydro*, *EVFlex* and *NoTES* cases. The modeling cases with 100% connection capacity result in the highest annual electricity exchange from the regional node to the city node. This is in line with the results showing a larger generation capacity on the regional scale with 100% connection capacity, and suggests that at least a share of the electricity exchange to the city energy systems stems from wind power generation. The *NoHydro* cases result in the highest value of local electricity generation on the city scale and, thus, the lowest electricity exchange from the regional to the city energy system. Fig. 6 shows the exchange of electricity per time-step (in GWh/h) between the regional and the city energy systems, sorted from highest to lowest, for the *Base* cases with 100%, 75% and 50% connection capacities. The connection capacity that is available is utilized to its maximum only during some time-steps with 100% connection capacity but during a large number of time-steps in the case with 50% connection capacity.

3.2. Costs

Local marginal costs are a good indicator of how expensive it is to utilize electricity and heat. Fig. 7 shows the average marginal costs of electricity in the city-scale and regional-scale energy systems for the different modeling cases. It is clear that limitations on the connection capacity have stronger impacts on the marginal

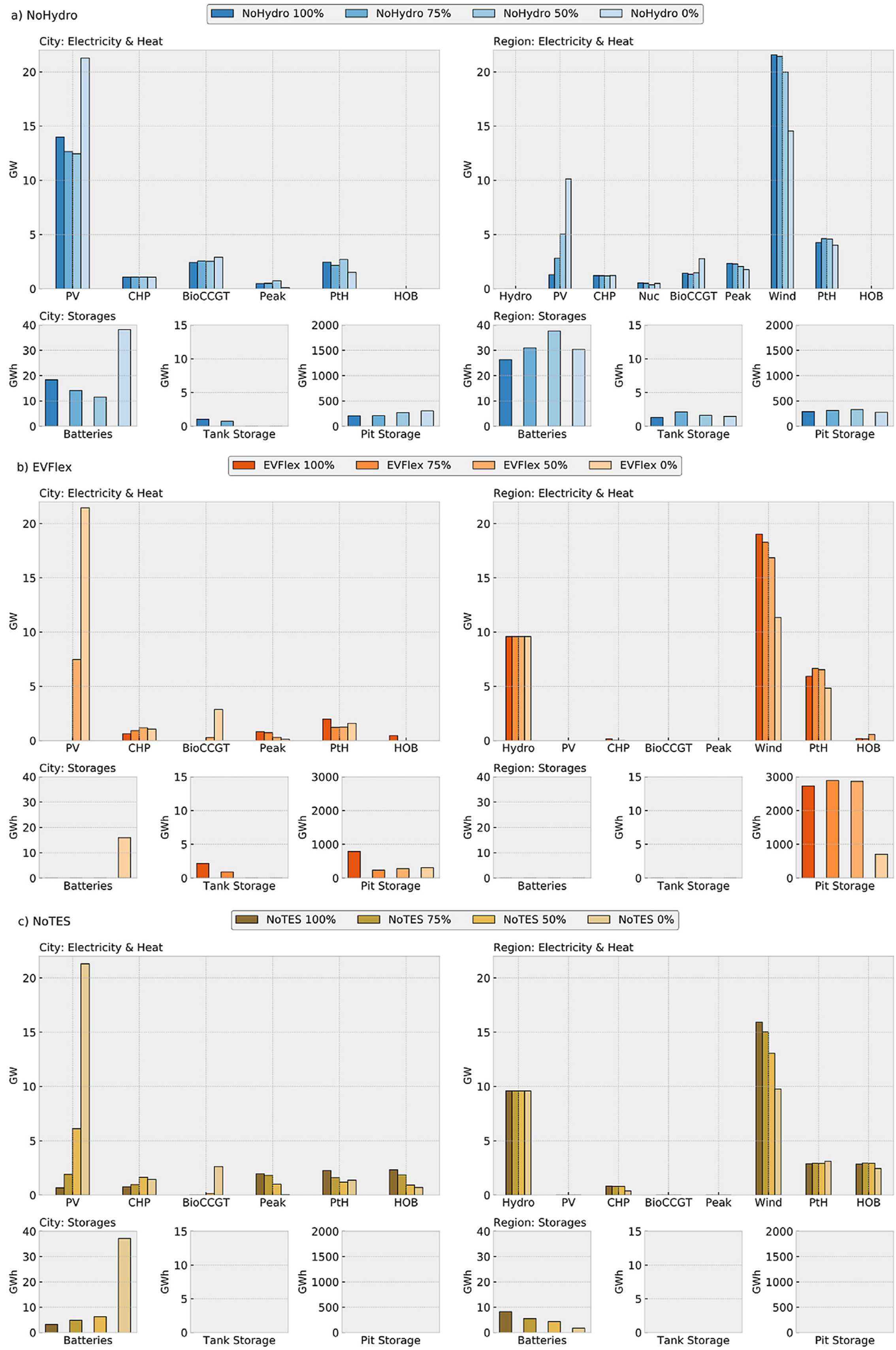

Fig. 4. Capacities for electricity and heat generation and storage technologies in the city-scale and regional-scale energy systems, for the cases of NoHydro (a), EVFlex (b), and NoTES (c) with 100%, 75%, 50% and 0% connection capacities. Notice the different scale on the y-axis for Pit storages in the EVFlex cases. CHP, combined heat and power plants (for which

costs of electricity in the city than on those of the regional energy system. In the *Base* cases, a 50% connection capacity results in almost 50% higher marginal costs on the city scale than does a 100% connection capacity. On the regional scale, the average marginal costs decrease slightly with lower levels of connection capacity between the scales (except for the *NoHydro* cases). This can be explained by the fact that less electricity is generated on the regional scale when the lower connection capacities preclude the export of electricity to the city scale and, thus, cheaper technology options are sufficient to supply the electricity demand. For the cases with 100% connection capacity, the average marginal costs for the city and regional scales are almost identical, as the electricity exchange between the two systems is not hindered by bottlenecks. The *NoHydro* cases show an overall higher level of marginal costs because the electricity needs to be generated by sources other than hydropower, i.e., mostly wind power, CHP plants and nuclear. (Observe that no investment costs have been considered for the hydropower present in the region, as explained in Section 2.2). The *EVFlex* cases exhibit the lowest average marginal costs on the regional scale, which is attributed to the introduction of car batteries at no cost to the electricity and heating systems. The average marginal costs for the *NoTES* cases are only slightly higher than those for the *Base* cases. On the city scale, the local marginal cost of heat is lower at low connection capacities, as compared to the case with 100% connection capacity. The local marginal costs of heat on the regional scale is not impacted by the connection capacity.

In Fig. 8, we show the total costs, i.e., the sum of the investment and running costs, for the energy systems on the two scales for all the modeling cases. Even though the evaluated scenarios are somewhat limited with regards to, for example, low-carbon-technology options and the connections to other price areas, the total system cost is a good estimation of the cost to Society for the decarbonized energy system designs on the city and regional scales. While the difference in average marginal costs for the city scale (in Fig. 7a) between the *Base* cases with 100% and 50% connection capacities amount to around 50%, the difference in total system costs between the two cases is only 3% (Fig. 8a). This implies that energy system designs with 100%, 75% or 50% connection capacities between the city and regional scales involve very similar costs for Society. However, with reduced connection capacity a larger share of these costs would have to be taken within the city energy system to ensure the city energy supply, as indicated by the higher average local marginal costs in Fig. 7. Currently the prices paid for electricity in cities do not reflect the local marginal costs of electricity. Such a pricing system that indicates the hourly costs of electricity supply within the city, however, could incentivize local electricity generation and facilitate the use of system flexibility in the city energy system. The same patterns of similar total costs for 100%, 75% and 50% connection capacities are seen in the *NoHydro*, *EVFlex* and *NoTES* cases.

4. Discussion

The system designs for the modeling cases with 50% and 100% connection capacities, though similar in terms of total costs, differ in that investments and measures towards the energy transition are applied by different stakeholders on different scales in the energy system. Today, many cities include in their strategies targets for increased local generation of renewable electricity, with the aim of creating a decarbonized city energy system. Projects to install local renewable electricity generation are usually planned and executed within the city and are, thus, valuable means for cities to accelerate and steer the local energy transition. Our modeling shows that for cities that aim for increased local electricity generation, a connection capacity of 50% is sufficient to ensure the fulfilment of the city electricity demand at total costs similar to those associated with 100% connection capacity, given that both the synergies with the city district heating system and the flexibility from storage systems are utilized. With rapid urbanization and increased electrification, it is not unlikely that growth in the city electricity demand will outpace the lead time for expansion of the connection capacity, i.e., power lines to the regional system. In the present analysis, we show that a system design with limited (50%) connection capacity between the city and regional energy systems, i.e., simulating the city energy system outgrowing the installed connection capacity, does not imply a more than 3% more expensive system design than with 100% connection capacity, but rather a redistribution of costs. The increase in local marginal costs in the model cases with 50%, as compared to 100%, connection capacity shows that with a lower connection capacity more of the investments and running costs are allocated to the city-scale energy system. Currently, electricity prices within city energy systems are not linked to the local marginal costs. Nonetheless, greater transparency in relation to the local costs of electricity could help to make investments in local electricity generation more attractive, especially in those cases in which bottlenecks leading to the regional energy system limit the electricity supply. In contrast, high local prices of electricity could hinder possibilities for city growth.

Our modeling includes system flexibility from the use of different storage systems and possibilities for sector coupling through the utilization of PtH technologies. In all the *Base* modeling cases, independent of the level of connection capacity, PtH technologies and thermal pit storage systems for seasonal storage are utilized. This highlights the importance of these technologies in district heating systems to enable synergies between the electricity and heating sectors. PtH technologies facilitate the uptake of electricity generation from local renewable sources, and pit storage systems allow for storage of thermal energy on much longer timescales than most other storage technologies for electricity or heat. As the share of varying generation from renewable energy sources such as solar or wind power is expected to increase in upcoming years these technologies present a low-cost option to handle variations in electricity generation in cities with district heating systems, specifically in the Nordic countries, where district heating is common. The impact from exploiting the flexibility in electric car charging is seen in the differences in the energy system compositions between modeling cases with smart charging opportunities for electric cars (i.e., the *EVFlex* cases) and those without this option. In order to utilize the large battery storage capacity that is available in electric cars for the benefit of the city energy system a charging infrastructure that allows for smart charging and V2G is essential. Additionally, an indication of the value of flexibility in the city during different times is required as, for instance, through a system with time-varying prices for charging.

Some consequences of the model setup should be considered when interpreting our results. We represent the city and the regional scales as a single node each in the modeling and thus, with one connection capacity limit between them. Bottlenecks in the connection between the city and regional scales, however, can occur on different voltage levels. To reach conclusions as to the power grid infrastructure of a single city system, a more detailed analysis is necessary. Nevertheless, our analysis compares the costs

the electricity generation capacity is plotted); CCGT, combined cycle power plants; Peak, gas turbines used for peak power generation; PtH, power-to-heat technologies, for which the heat generation capacity is plotted; HOB, heat-only-boilers (except electric boilers which are included in PtH).

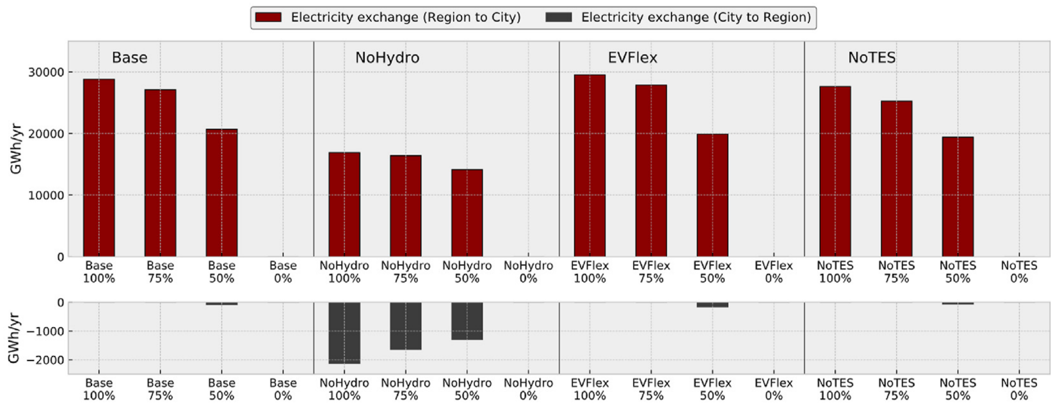

Fig. 5. Annual levels of electricity exchange between the regional and city scales, for all the modeling cases and the different levels of connection capacity, as obtained from the modeling.

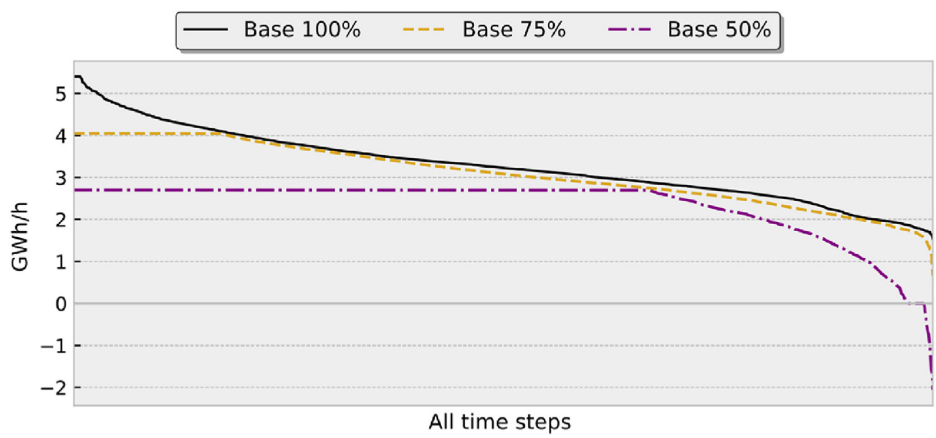

Fig. 6. Duration curves for the exchange of electricity (GWh/h) between the regional and city scales in the Base cases with 100%, 75% and 50% connection capacities, where the positive y-axis indicates the electricity exchange from the regional scale to the city scale.

and system designs while considering different levels of connection capacity and, thus, can inform decision makers as to the value of grid expansions between city and regional scales. The focus of this work is not the potential bottlenecks within city energy systems, as those require a more detailed representation of the spatial distribution of the energy supply and demand within the city energy system. We have chosen to model energy technologies on city and regional scales with the same investment costs. Economies of scale could imply lower investment costs for larger installations on the regional scale. However, investments on a smaller scale can, to a greater extent than investments on a regional scale, be driven by non-monetary motives. Such motives can for example be an interest in contributing to the energy transition through installing low-carbon technologies in buildings or becoming more energy self-sufficient. We aggregate three cities into a single modeling node and, due to a lack of other data, use the same district heating profile to represent all three cities. The utilization of only one profile results in the peaks in heating demand occurring at the same time in all three cities. If real demand profiles for each city were instead used, it can be assumed that some of these peaks would be smoothened due to temperature differences between the different locations. This, however, would be expected to have impacts mainly on the investment in heat-only boilers and on the operation of PtH technologies.

The challenge of sufficient power grid infrastructure to enable electricity import to fast-growing cities is, in this work, reflected through modeling cases with different connection capacities that all use the same energy demand profiles. Urbanization and city growth are expected to increase energy demands, this trend is, however, counteracted by energy efficiency targets (possibly enhanced by the proposed EU “energy efficiency first” principle). In addition, temporal and spatial distribution of energy demands will also be influenced by a change in demand. Our study aggregates the three largest cities of a region into one modeling node and can, thus, not capture the differences in population increase between the different cities, or the impacts of building new districts and neighborhoods, which are likely to include stricter energy efficiency standards.

We model Year 2045 with a constraint on zero emissions from electricity and heat generation. All three cities that are modeled in this work have formulated aims to reach similar goals earlier than 2045. Yet, the cities' possibilities to act will be different in different sectors, where the developments of the electricity and transportation sectors are dependent on national and EU policies. Our results indicate that installations of solar PV and power-to-heat technologies are important to reach these targets in the city-scale energy system. Additional flexibility can be provided by thermal energy storage systems and batteries. While our study utilizes cost assumptions for Year 2045, all these technologies can be installed in city energy systems prior to 2045 to meet the cities' energy targets of ‘renewable electricity and heat generation’ in Gothenburg and ‘fossil-free’ energy systems in Stockholm and Uppsala. Our

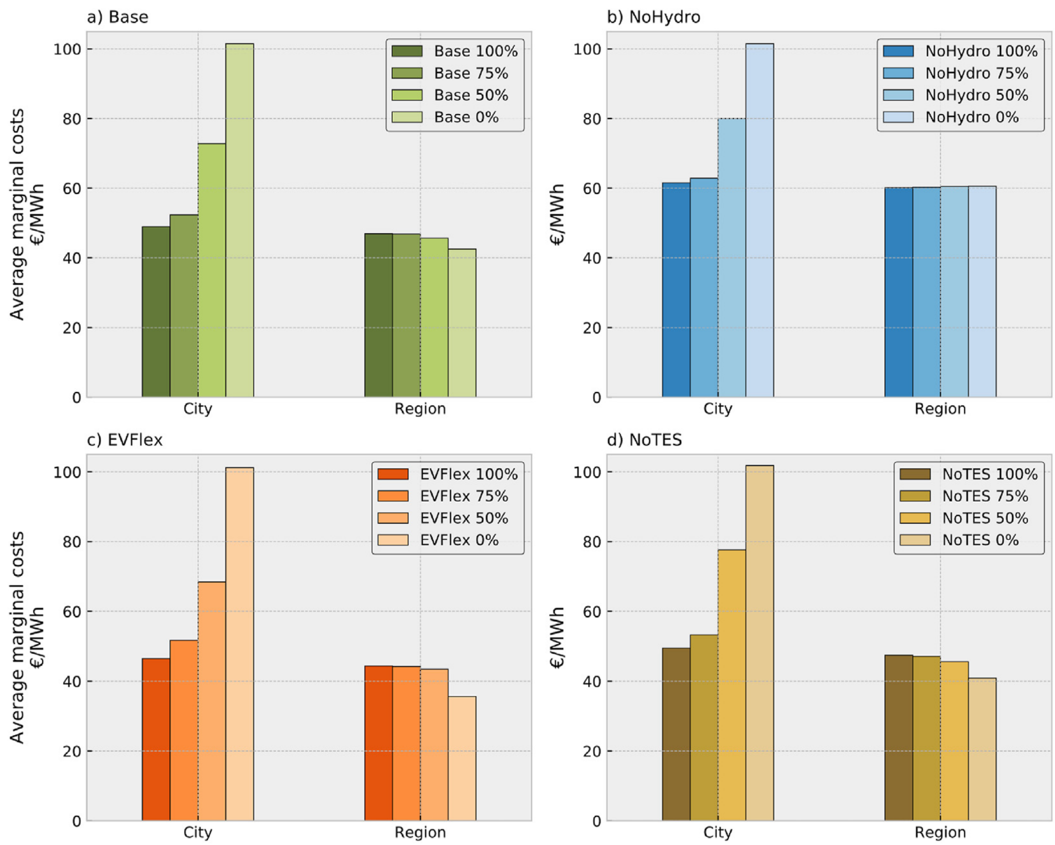

Fig. 7. Average local marginal costs of electricity in the city-scale and regional-scale energy systems and for the four levels of connection capacity in the: Base cases (a); NoHydro cases (b); EVFlex cases (c); and NoTES cases (d), all as obtained from the modeling.

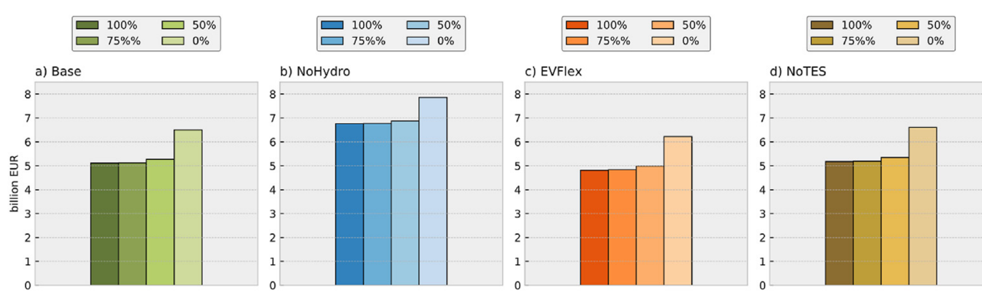

Fig. 8. Total system costs in billion EUR (1000 MEUR) for the modeled: Base cases (a); NoHydro cases (b); EVFlex cases (c); and NoTES cases (d). Total costs are the sum of the fixed and variable operational costs and the annualized investments costs of all energy technologies for one model year.

modeling shows, that the designs of such systems involve CHP and peak power technologies, which frequently are already in place in city energy systems and could be run on biofuels, in addition to the beforementioned installment of solar PV, PtH technologies and storage systems.

This work could be extended to include the effects of growth estimates and planned city expansion projects in the three different cities. Additionally, case studies could be designed to assess the energy targets formulated in each city, as well as different assumptions on energy efficiency measures.

5. Conclusions

This paper reveals the impacts of different levels of the connection capacity between city- and regional-scale energy systems on the design, operation and costs of the systems. We investigate cases with connection capacities equal to 100%, 75%, 50% and 0% of the maximum hourly annual electricity demand on the city-scale. While the energy systems with 100% and 50% connection capacities between the two scales differ by only 3% in terms of the total costs, they involve different levels of installed generation capacity in the city and regional energy systems. This means that investment in and operation of an energy system with increased local, city-scale generation to supply growing cities with electricity entail a total cost similar to that of a system that relies on greater connection capacity and increased power generation outside of the cities. The modeling does not include costs for investment in connection capacity; such costs and the associated lead time for connection capacity expansion need to be evaluated against the cost and preferences linked to the different energy system designs.

At lower connection capacities, a larger share of the cost is distributed to the city energy system, i.e., more of the investments are taken at city scale. As the city-scale energy systems are smaller in terms of electricity demand than the regional-scale energy systems, the redistribution of investments to the city scale results in higher marginal costs for electricity in the city energy system in cases with lower connection capacity (i.e., a smaller increase in marginal costs with 75% and a larger increase with 50% connection capacity). High local costs of electricity may limit possibilities for growth, especially with respect to the establishment of new businesses and small-scale industries on the city scale. This is an effect that would need to be addressed through a redistribution of costs or other adequate policy measures or tariff systems. The modeling does not show the same effect on the marginal costs of heat inside the city energy system, which implies that the electricity sector on the city scale has to take on the largest share of the cost when the connection capacity between the city and regional systems is more limited. We find that the variable electricity exchange to the city system and PtH technologies on the city scale in the modeling are partly used to balance wind power fluctuations on the regional scale, albeit only when the necessary connection capacity is available. Our work shows that fast-growing cities, in which challenges with power grid infrastructure limitations for electricity import to the city energy system exist, can instead of, or as a complement to grid expansions increase the use of local energy technologies and realize the potentials for flexibility from synergies between sectors and from smart charging of electric cars.

Authors' contributions

Conceptualization: V.H., L.G.; Methodology: V.H., L.G.; Formal analysis, Visualization, Data acquisition: V.H.; Writing - original draft: V.H.; Writing - review and editing: F.J., M.O, L.G., V.H.; Funding acquisition: M.O., F.J.; Supervision: F.J., M.O., L.G.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2021.100041.

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