

Article

Evaluating Spatial Interdependencies of Sector Coupling Using Spatiotemporal Modelling

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Abstract: In light of global warming and the energy turn, sector coupling has gained increasing interest in recent years, from both the scientific community and politics. In the following article it is hypothesized that efficient multifaceted sector coupling solutions depend on detailed spatial and temporal characteristics of energy demand and supply. Hence, spatiotemporal modelling is used as a methodology of integrated spatial and energy planning, in order to determine favourable sector coupling strategies at the local level. A case study evaluation was carried out for both central and decentral renewable energy sources. Considering the high temporal resolutions of energy demand and supply, the results revealed a feasible operation of a district heating network in the central areas of the case study municipalities. Additionally, building integrated solar energy technologies are capable of providing large amount of excess energy that could serve other demand sectors, such as the mobility sector, or could be used for Power-to-X solutions. It is suggested that sector coupling strategies require spatial considerations and high temporal comparisons, in order to be reasonably integrated in spatial and urban planning.

Keywords: integrated spatial and energy planning; energy system integration; district heating; smart energy systems; solar energy; wastewater heat recovery; excess energy



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1. Introduction

Sector coupling (SC) emerged as a key strategy for increasing energy efficiency, in order to substitute fossil energy sources, to economically decarbonize the energy system [1–3], and finally, to reach global and national climate targets. Many studies understand SC as a means of tackling global warming. Gielen et al. [4] recently evaluated the role of renewable energy towards energy transformation and suggested focusing on SC and corresponding infrastructural challenges, including the role of charging electric vehicles, grid reinforcements, smart grids, and the challenges of demand shifts. Wu et al. [5] propose an emphasis on the interrelation and coupling of different energy vectors like electricity, natural gas, hydrogen, heating or cooling, simultaneously taking into account different spatial scales. Apart from the call for a more integrated approach of energy system planning, Van Nuffel et al. [3] imply that SC can finally contribute to reducing the costs of decarbonising the energy system. Already in the “Energy Roadmap 2050” [6], significant pressure on the energy system is predicted, due to its substantial contributions to global CO₂ emissions. In order to transform the energy system, infrastructure and grid investments as well as additional

utilization of electricity, particularly for the decarbonisation of the demand sectors transport, heating and cooling, were suggested. Moreover, energy savings, increasing use of renewable energy sources (RES), including an expansion of electricity storage systems and further interactions between decentralised and centralised energy supply systems were highlighted [6]. This shows that essential elements of SC were recognized early and that the idea of SC was continuously pursued.

1.1. Different Concepts of Sector Coupling

Within the scientific community, there are different concepts of SC, as a universal definition is still pending. In a comprehensive characterisation, Wietschel et al. [2] distinguished between three general perspectives of SC:

- Sectoral: Primarily referring to sectors of energy consumption like households, commerce, industry, service, or transportation.
- Technological: Focusing on technical solutions like heat pumps, district heating, or electric vehicles.
- System and infrastructure: Interlinking electricity, heating, cooling, mobility, and industrial processes through corresponding infrastructure.

Based on this differentiation, SC is defined as a continuous process of substituting fossil energy sources with renewable electricity or other renewable energy sources, by also integrating alternative types of renewable energy supply like waste heat. Moreover, already existing and new cross-sectoral applications need to be endorsed. In this sense, an energetic interlinkage between sectors of energy consumption via grid infrastructure is also necessary [2]. Lund et al. [7] approach SC with the concept of “smart energy systems” that goes beyond independent energy grids and covers sectors like electricity, heating, cooling, industry, buildings and transportation. Similar to Wietschel et al. [2], they argue that emphasis should be laid on the integration of all energy-related sectors, as well as on the associated infrastructure.

Another term often related with SC is energy system integration. Hanna et al. [8] (p. 4) described the concept as “connecting a wide range of energy services and systems together to maximise energy use and minimise waste”. They further elaborate the following central ideas of energy system integration:

- Optimisation of energy use by automation, communication and energy storage systems.
- Combination of multiple energy vectors like electricity, gas, hydrogen, heating or cooling.
- Power-to-X solutions as a linkage between different energy vectors.

Power-to-X further comprises specific sector coupling benefits such as the transformation of electricity into hydrogen, methane and methanol, or utilising electricity for NH₃ or H₂O₂ generation [9]. Wu et al. [5] remark the challenge of coupling energy vectors on various spatial scales, from international to building levels, as well as considering coupling technologies like combined heat and power, Power-to-Gas or heat pumps. Additional advantages like utilising synergies between energy vectors, increasing efficiency and flexibility of the energy system, consequently resulting in CO₂ reductions, and further inclusion of local RES in the energy system are declared [5]. This is in line with the overall objective of SC, as described in Wietschel et al. [2], aiming for the reduction of greenhouse gas emissions through the substitution of fossil energy.

From a European perspective, the Integrated Strategic Energy Technology (SET) Plan [10] questions the rather vertical technology-specific focus of the energy transition, and emphasises moving towards a horizontal and integrated approach, advancing a more flexible and resilient energy system. In this context, the fourth action of the SET plan aims for flexibility in thermal energy generation, demand response and storage systems, as well as “... efficient heating and cooling technologies (such as heat pumps and combined heat and power) to use synergies between energy vectors ...” [10] (p. 11). Commissioned by the European Parliament, Van Nuffel et al. [3] further argue that from an economical point of view, the decarbonisation of the energy system is only possible by coupling different

parts of the energy system. It is further distinguished between “end-use sector coupling” and “cross-vector coupling”. The former mainly focuses on the electrification of supply and demand, whereas the latter encompasses an integrated approach, embracing energy vectors like electricity, heat or gas. Cross-vector coupling includes, for example, Power-to-X solutions or the utilisation of waste heat for district heating.

Finally, as a cornerstone of the European Green Deal, the European Commission recently defined energy system integration as “the coordinated planning and operation of the energy system ‘as a whole’, across multiple energy carriers, infrastructures, and consumption sectors” [1] (p. 1) and specified three core concepts [1]:

- Circular energy systems with a focus on energy efficiency.
- Utilisation of low-carbon fuels like hydrogen for specific end-use sectors.
- Multi-directional energy system, empowering consumers.

Based on these core ideas, the European Commission correspondingly presented an action plan on how to reach energy system integration. On a political level SC, or energy system integration, respectively, is getting more attention, if not even moving into the centre of energy transition. Throughout this paper, the term SC also refers to energy system integration. Since SC incorporates many different concepts and approaches, the authors support the recent communication on energy system integration [1] from the European Commission. However, in order to realise SC, certain prerequisites must be given, expedient strategies need to be developed, and feasible planning is required. This is where we suggest that Integrated Spatial and Energy Planning and its methods like spatiotemporal modelling, further explained hereinafter, play a significant role.

1.2. Integrated Spatial & Energy Planning and Spatiotemporal Modelling

Integrated spatial and energy planning (ISEP) is defined by Stoeglehner et al. [11,12] as an integral part of spatial planning, comprehensively engaging with the spatial dimensions of energy demand and supply. ISEP relates to three main fields of action:

- Energy-efficient spatial structures: Focus on multi-functionality, appropriate density, minimum size and compact organization.
- Renewable resources and spatial structures: Considering aspects of resource logistics, siting of energy-related technologies and grid infrastructure, as well as the temporal availability of RES.
- Energy supply systems tailored to spatial structures and vice versa.

Due to the stationary character of settlements, proactive planning in the context of ISEP can play a vital role for the energy turn. A closer look at the spatial dimension is essential to set actual measures related to utilizing available RES, determining the actual energy demand on-site, or connecting different energy domains [11].

Besides the spatial dimension, the temporal pattern is also crucial. For instance, over the course of a day, the energy demand in residential areas might significantly differ from industrial areas. Another example is energy provision via solar energy, with generation peaks during the day and no generation during nights. In this context, spatiotemporal modelling (STM) became more noticeable in research during the past ten years, dealing with the spatial and temporal patterns of energy supply and demand [13]. International applications of STM stretch from evaluating building energy demand schemes in neighbourhoods and districts in Switzerland [14] to simulating the renewable electricity mix in Brazil [15], or analysing wind and wave energy along the Norwegian coastline [16]. In addition, STM was also specifically applied as an appropriate methodology of ISEP. Spriet et al. [17], in the context of wastewater heat recovery, Ramirez Camargo et al. [18] for electricity provision via photovoltaic panels, or Ramirez Camargo and Stoeglehner [13] in a holistic review for municipalities. Ramirez Camargo and Stoeglehner [13] depict that after considering temporal conditions, merely a fraction of the locally available RES could properly supply the demand. They further argued that a diversification of energy technologies is beneficial for the quality of RES utilisation. This is especially interesting, since the diversification of

RES, the spatial and temporal interdependencies, as well as integrated planning, underpins the necessity to deepen the interlinkage between SC, ISEP, and STM.

1.3. Research Demand

Recent studies mainly focus on the technical aspects of SC, such as infrastructure optimisation [19], SC facilities [20], or SC solutions like demand and response systems [21]. Other research also tried to include economic considerations of SC [3]. Another example is the work of Jalil-Vega et al. [22], who developed an optimisation model for urban energy systems and evaluated scenarios for heating, cooling, electricity, and transport. The investigations were carried out for spatially delimited zones and the research urges for a spatial differentiation when it comes to energy system planning. However, such studies lack the primary engagement with SC. As research did not treat the spatial dimension of SC in much detail, the following paper tries to fill this gap, and attempts to reveal spatial interdependencies of sector coupling, using methods of ISEP. More specifically, STM is used to show the spatial and temporal linkage between energy demand and energy provision. In addition to examining the spatial dependencies of relevant energy infrastructure, the linear approach between a specific energy source and a single sector of energy demand is also questioned. The novelty of this research lies in linking SC, spatiotemporal modelling and spatial planning, as not only the spatial and temporal context of energy provision and energy demand is evaluated but also strategies on incorporating SC in integrated spatial and energy planning are derived. In this way, added value for spatial planning practice could be deduced, which is another unique feature of this study.

It is assumed that for a successful implementation of SC, the planning complexity increases and more holistic and integrated planning is required. In this context, it is further hypothesised, that multifaceted SC solutions depend highly on spatial structures as well as on temporal patterns of energy demand and supply, and that these interdependencies are essential to be considered for increasing the energy efficiency of the whole energy system and to move towards energy transition. Therefore, the questions addressed in this research are:

- What influence do spatial and temporal conditions pose on successful implementation of sector coupling?
- Based on the application of a spatiotemporal model on the (inter)municipal level, what favourable sector coupling strategies could be derived?

In order to answer the research questions, the concept of sector coupling is further elaborated and the used spatiotemporal model, as well as the case study where the model is applied, are described. The first part of the results section shows the possible SC paths via central renewable heat supply and the second part comprises the coupling of decentral energy supply solutions. Finally, the case study results are discussed, the relevance of sector coupling for spatial planning is deduced and the strengths and limits of the methodology are highlighted.

2. Methods and Materials

The overall methodological approach of this research is split into three segments (see Figure 1). First, the system design for SC is specified. The systemic considerations are intended to show the concept of SC from an interdisciplinary perspective, as the team of authors is affiliated with spatial planning, energy planning, remote sensing, spatial analysis, and sanitary engineering. Furthermore, system boundaries of the methodology are delimited. Second, the STM is defined. Here, the energy demand and energy provision in high spatiotemporal resolution are calculated, from which relevant indicators for SC can be derived. Third, the specified methods are applied in a case study, which represents the final part of this chapter. The results of the case study application are finally used to show options on how to successfully implement SC and to derive strategies for SC.

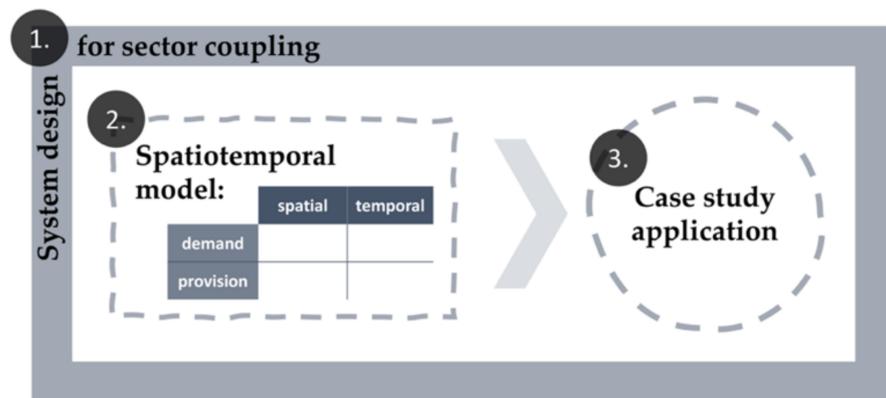


Figure 1. Visualisation of the methodological approach.

2.1. System Design for Sector Coupling

In this paper, it is hypothesized that SC is embedded and strongly interdependent with the spatial conditions that exist. Hence, the focus is on spatial interdependencies at the local level. There are different reasons for choosing the local level. For instance, thermal energy cannot be transported across large distances (compared to electricity), due to energy loss through transportation [23]. As a result, thermal energy is restricted to local use, underlining the necessity of evaluating the spatial distribution of energy sources and sinks. However, large-scale photovoltaic or wind power plants require specific siting, e.g. due to electricity network capacities and environmental considerations. Hence, in terms of a holistic evaluation, the local level offers the opportunity to include all types of energy provision, corresponding infrastructure, and associated sectors of energy demand.

The holistic approach of “cross-vector coupling” (see [3]), interlinking energy vectors such as electricity, and heat or the utilisation of waste heat, was taken as an underlying idea for the system design. In addition, the SC design also reflects the systemic and infrastructure-based approach, as well as the technical and sectoral considerations described in Wietschel et al. [2]. As a result (Figure 2), the authors anticipate spatial interdependencies of SC among three subdivisions.

(1) *Energy provision through central and decentral RES:* The focus of this research lies in renewable energy provision only. More specifically, already established, universally used and rather easily accessible RES are distinguished. Hence, Figure 2 illustrates the categorisation in bioenergy, hydropower, wind power, ambient energy, solar energy and geothermal energy. A differentiation between central and decentral RES is generally intended, but not visualised in the illustration. In the context of this article, single-point sources (e.g., industrial waste heat) are considered as central RES and multi-point resources (e.g., spatially distributed building integrated solar energy) as decentral RES. Point of departure, in order to show the feasible paths of SC in combination with the applied STM at the local level, is the outlined renewable energy provision.

(2) *Relevant infrastructure, including grid and storage systems:* As illustrated in the centre of Figure 2, grid-based infrastructure like district heating, electricity grids and gas grids were selected as essential to link RES provision and the sectors of energy demand. Further relevant technologies are for instance energy storage systems, combined heat and power units or Power-to-X solutions.

(3) *Sectors of energy demand:* Finally, sectors of energy demand are differentiated into residential, services, industry, mobility, agriculture and forestry. It is specifically not referred to the term “end-use sectors”, which is broadly used in research and politics. The reason for this is, that in a circular economy, the term end-use is misleading. It is important to highlight, that the system design for SC, as presented in this paper, can be adapted. However, it is intended as a guide through the rather complex matter of SC.

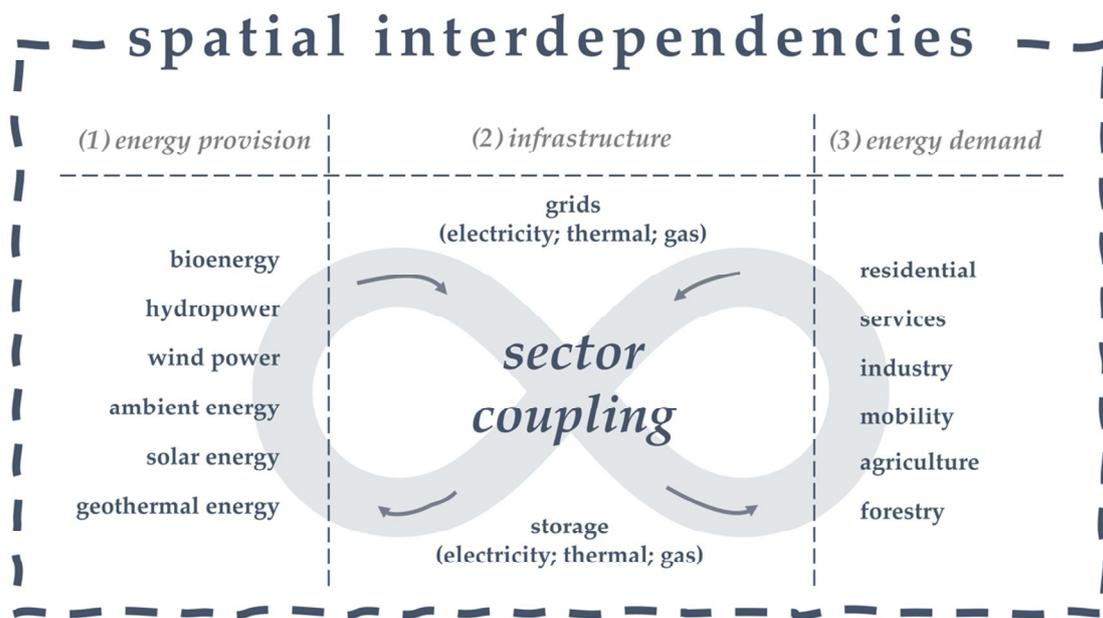


Figure 2. General system design—embedding sector coupling into spatial interdependency (own illustration based on [3,8]).

Additionally, the intended system design is illustrated by the following SC examples: Electricity for instance, can be locally provided through photovoltaic (PV) installations on residential or commercial rooftops. Besides the direct use of electricity, multiple other sectors can be serviced. The generated electricity could be utilised for the operation of heat pumps and consequently for space heating [24] or for charging of electric vehicles [25]. An alternative (but still widely unconsidered) option of central and local renewable energy provision, is the utilisation of excess heat available in the wastewater infrastructure. This concerns waste heat from sewage gas (biogas) combustion at a wastewater treatment plant (WWTP) and/or the intrinsic thermal energy content of (treated) wastewater in the WWTP's effluent [26,27]. Wastewater heat recovery might even take place in the upstream sewer system [28]. Likewise, other types of waste heat from industrial processes to feed district heating systems are possible. By incorporating heat cascades, the generated thermal energy can be further used in supplementary sectors like agriculture or forestry [29].

2.2. Spatiotemporal Model

Spatiotemporal models deal with the spatial and temporal components of energy demand (ED) and energy provision (EP). In spatial planning practice, the spatial dimension is a key parameter when it comes to the application of instruments and the preparation of plans. Spatial categorisations often follow geographical or political conditions. More specifically, administrative boundaries or statistical units are the most accessible to use. Furthermore, taking national or regional energy statistics as examples, the most common time horizon is a year. Another prominent example are time series of energy demand, with a quarter-hourly resolution derived from synthetic load profiles for electricity trading (e.g., [30]). Depending on the task at hand, increasing the temporal and spatial resolution leads to more accurate results, simultaneously increasing the data processing efforts. For example, hourly energy demand values provide insight into demand patterns that are otherwise hidden in the daily, monthly or annual total. This chapter describes the procedure used in this research, regarding both spatial and temporal components of ED and EP, within the spatiotemporal model. First the evaluations of the ED are described in more detail, which is then followed by a description of the EP procedure and the evaluations of specific spatiotemporal indicators.

Energy demand: The ED (both thermal and electric) can be prepared and pre-processed on different spatial and temporal levels (see Figure 3). Statistical data concerning living

areas, cultivated areas and employees, serve as a basis to calculate the energy demand of the municipality and of 250-m raster cells. The applied methodology is described in detail in Abart-Heriszt et al. [31]. In addition to residential ED, STM also takes into account the demand of other sectors like services, industry, agriculture and forestry.

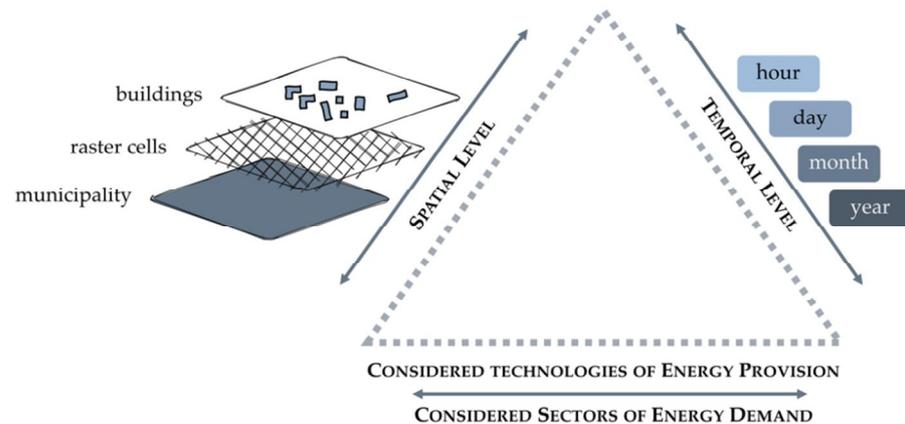


Figure 3. Overview of the spatial and temporal levels of concern, including the considered technologies of energy provision and sectors of energy demand (own illustration).

The building level represents the highest spatial resolution. Relevant calculations were based on the register of buildings and dwellings. Information derived from this database were building-specific coordinates (easting and northing), building type, specific living area, building period, as well as principal and further residence. This database, in accordance with the methodology described in Abart-Heriszt et al. [31], was used to calculate the annual energy demand of each residential building in the research area. The energy demand was divided into two categories—(i) single-family houses, semi-detached houses and terraced houses, and (ii) multi-storey buildings. In addition to this differentiation, the heating demand was further split into space heating and hot water preparation.

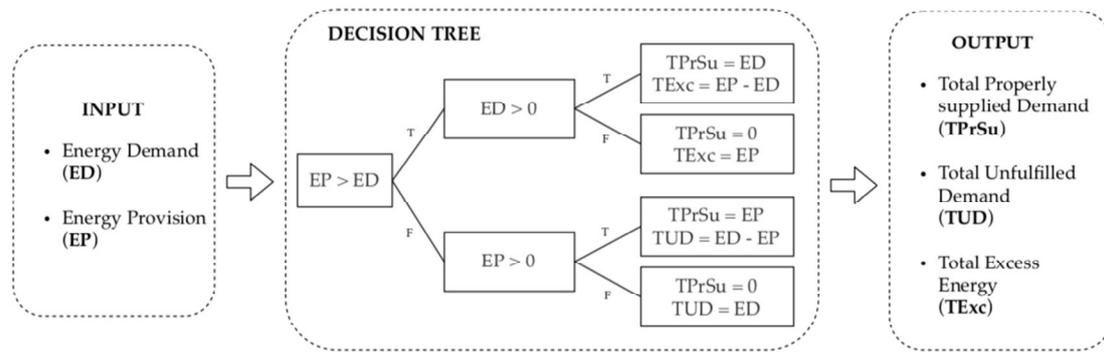
For high temporal resolution, the annual electricity demand (ED_{el}) was transferred into hourly demand time-series by applying synthetic load profiles of APCs [30]. Using a typical test reference year provided by the Austrian “Zentralanstalt für Meteorologie und Geodynamik” and based on the methodology of Eichlseder & Almbauer [32], the hourly time-series of the heating demands (ED_{th}) could be calculated. Besides hourly temperature values, the test reference year also included the radiation time-series. The hourly time-series of the ED were taken as a basis to further conduct comparisons with hourly, diurnal, or monthly EP values (see Figure 3).

Energy provision: Starting from building integrated decentral $EP_{th,el}$ (e.g., photovoltaic, solar thermal systems or air-heat pumps) up to central $EP_{th,el}$ (e.g., waste heat recovery from industrial processes, biomass plants or large-scale wind farms), the provision of renewable energy is a rather diverse matter. However, with respect to the STM, hourly, diurnal or monthly time-series of energy yields were calculated and used for the direct comparison between $EP_{th,el}$ and $ED_{th,el}$, and consequently for the derivation of the spatiotemporal indicators.

Spatiotemporal indicators: The final realisation of the STM and corresponding indicators, followed the work of Ramirez Camargo et al. [18] and Ramirez Camargo and Stoeglehner [13]. Figure 4 visualises the input parameters and the calculation process in the form of a decision tree, in order to determine the output parameters of the model. Input parameters were both ED and EP in high temporal resolution, from which three relevant indicators could be calculated as an output. Throughout the modelling process, a differentiation between thermal energy (th) and electricity (el) was followed. If not specifically referred to either thermal energy or electricity, the term ‘energy’ refers to both.

Using hourly/diurnal/monthly time-series of ED and EP, three main spatiotemporal indicators were calculated as outputs (as illustrated in Figure 4). The first relevant spa-

tiotemporal indicator was the Total Properly Supplied demand ($TPrSu_{th,el}$), representing the amount of ED that was directly met by renewable EP at the investigated time. The Total Unfulfilled Demand ($TUD_{th,el}$) exemplifies the amount of energy that is to be provided by another RES, from storage or the grid, respectively. Finally, the Total Excess energy ($TExc_{th,el}$) represents the amount of energy that cannot be used immediately and must therefore be either stored or fed into the respective energy grid [18].



Note that in this visualisation it is not specifically referred to either thermal energy or electricity

Figure 4. Overview of the applied spatiotemporal model (adapted after Camargo et al., 2015).

2.3. Case Study Description

The third section represents the materials, as the analyses were carried out in two municipalities in the province of Upper Austria. “Wallern an der Trattnach” with 3028 inhabitants, covering an area of 14.6 km² as well as the neighbouring municipality “Bad Schallerbach”, with 4214 inhabitants and an area of 8.5 km², respectively [33]. “Bad Schallerbach” shows higher building densities and is characterised by a more compact settlement structure. As illustrated in Figure 5, the municipalities are located approximately 30 km southwest of the provincial capital Linz.

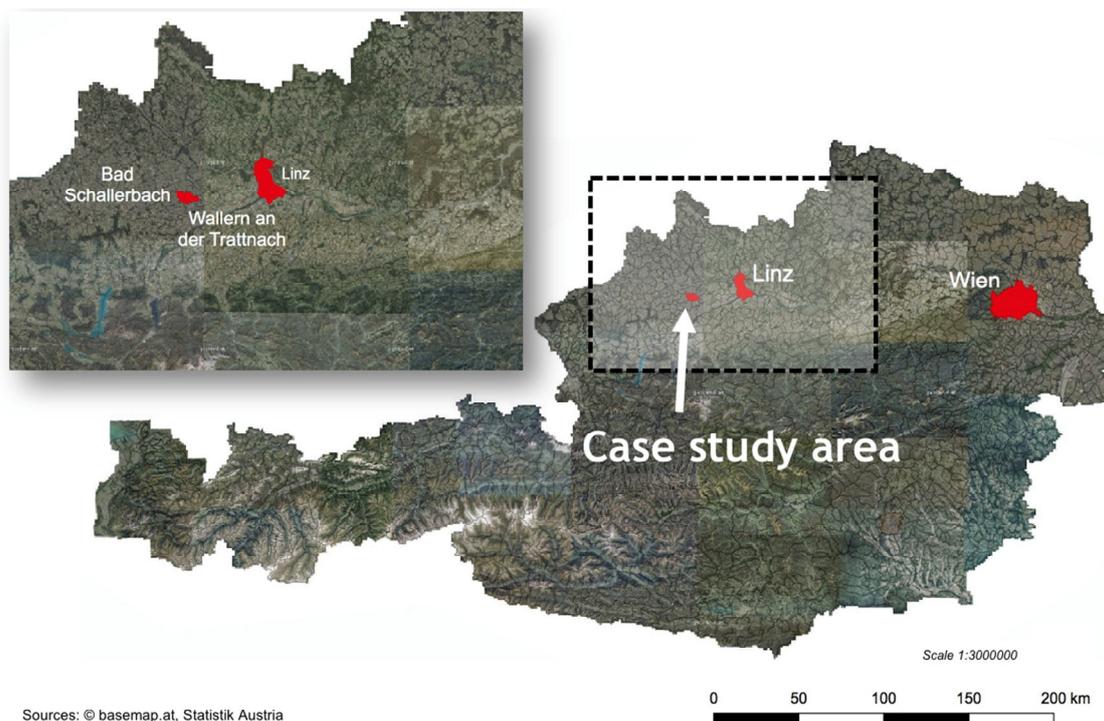


Figure 5. Location of case study area (own illustration).

Energy demand in the case study area: Based on the spatial analyses of the “Energy Mosaic Austria”, the sector-specific total energy consumption of the case study municipalities is illustrated in Table 1. The “Energy Mosaic Austria” is a freely available nationwide energy and greenhouse gas inventory developed by Abart-Heriszt et al. [31,34]. In “Bad Schallerbach”, the highest energy consumptions were calculated for the mobility sector, followed by the residential, service, industry and agricultural sector. In “Wallern an der Trattnach”, the industrial sector comprised the highest consumption values, followed by the residential, mobility, service and agricultural sectors. Total greenhouse gas emissions (GHG) of both municipalities were estimated at 51,610 t CO₂-equivalents and should be reduced by 37,710 until 2050. Currently, in terms of energy provision, approximately 75% was provided by fossil energy compared to 25% RES [31,34].

Table 1. Sector specific total energy consumption [MWh/a] of the case study municipalities [31,34].

Municipality	Total	Residential	Agriculture	Industry	Services	Mobility
Wallern an der Trattnach	92,800	27,300	2800	33,700	8400	20,500
Bad Schallerbach	112,100	33,800	1000	11,300	25,800	40,300

The presented municipal energy demands serve as a basis to further increase the spatial resolution to the raster and building level, in accordance with the description in Section 2.2. Energy related data from municipal buildings was provided by the local authorities of the case studies.

RES potentials in the case study area: Building integrated photovoltaic (PV) and solar thermal (ST) systems were chosen as decentral energy provision technologies in the case study, using roof-tops of buildings as a basis. The reasons for the commitment to these two technologies were the rather straightforward installation on roof-tops of private and public buildings and the avoidance of additional land use. The bottom-up approach, starting from roof-tops of buildings, could be projected to certain settlements or to the entire municipality. Hourly PV yield calculations were performed in accordance with the method described in Ramirez Camargo et al. [18]. ST yields were assessed using the approach explained in Carpaneto et al. [35]. Roof-top areas were computed, using a digital elevation model with a 1-m resolution. Furthermore, a minimum area of 4 m² was chosen for ST installations and 8 m² for PV, respectively. Depending on the chosen technology of solar cells and efficiency parameters, PV provision could vary substantially. As it was not the intention to overestimate total PV provision, a cautious calculation was chosen. Further, five categories of exposition were distinguished—north, east, south, west and plain. The slopes were computed between 20° and 50° and <20° for flat roof-tops. In order to compute the solar radiation time-series for the roof-top areas, the solar irradiance and irradiation model “r.sun” [36] was applied, also taking into account the shadowing effects from the landscape and buildings. Hourly solar radiation values were derived from a test reference year. The spatiotemporal indicators were calculated in 20 percent steps of available roof-top areas. This approach allows a variation of roof-top areas for PV and ST systems, as well as the spatial differentiations between individual buildings and entire settlements. In the research area, the ten-year average annual irradiation on a horizontal plane was estimated at 1170 kWh/m² [37]. Taking into account all relevant roof-tops in both municipalities, approximately 256,000 MWh/a of heat and 40,000 MWh/a of electricity could be provided. However, it was assumed that a utilisation of all roof-tops for solar energy generation is neither reasonable nor economically viable. Therefore, spatiotemporal evaluations are vital.

The local WWTP is situated, in the north-eastern part of the research area, to which both investigated municipalities are connected. As already mentioned before, in the water sector in general, and here specifically, WWTPs play a major role in SC (e.g., [20]). This is because WWTPs not only require different energy vectors for wastewater and sewage sludge treatment purposes, but are frequently also capable of providing surplus energy

(mainly heat, occasionally also biogas or electricity). Hence, they could be understood as SC-facilities. In this context it should be highlighted, that the European Parliament [38] recently recognised wastewater as RES, primarily due to its thermal energy content. To account for this development, available surplus energy from the WWTP is taken as a starting point for SC and as the central EP_{th} solution, in the case study evaluation. The WWTP and the described municipalities in its catchment area also recently represented the Austrian pilot site of the INTERREG Central Europe project “REEF 2W—Increased renewable energy and energy efficiency, by integrating, combining and empowering urban wastewater and organic waste management systems” (<https://www.interreg-central.eu/Content.Node/REEF-2W.html>) (accessed on 07 January 2021). Respective findings of the REEF 2W investigations are summarised in [39]. They provide the basis for the SC and STM-related evaluations presented in this article.

The local WWTP has a capacity of 74,000 population equivalents (PE). The mechanical pre-treatment comprises two parallel screens, a combined sand and grease trap, and a primary clarifier. The biological wastewater treatment step applies the activated sludge process in two parallel aeration basins and four secondary clarifiers. Excess sludge stabilization takes place in two digestion towers [40]. Today, the available digester gas (biogas) is used in a combined heat and power (CHP) generation unit, to primarily cover WWTP internal electricity and heat demand (wastewater and sludge treatment purposes, supply WWTP buildings). In addition, a private building in close vicinity is also being heat supplied by the WWTP. However, according to Zach et al. [39], about 177 MWh of the available thermal energy remained unused in the year 2016. Furthermore, the effluent of the WWTP contains significant amounts of (so far untapped) heat. Considering the years 2016 and 2017, the annual average wastewater inflow at the WWTP was around 6 million m^3 , the annual average wastewater in the effluent of the WWTP was about 14.3 °C. By cooling the effluent by 2 K, an annual heat recovery potential of around 14,000 MWh is realisable [39]. From a technical point of view, even higher degrees of cooling would be possible. In this context, it needs to be clearly stated, that we only consider and recommend the effluent/outlet (after secondary clarification) as a suitable location for wastewater heat extraction at WWTPs. This would assure that the energy recovery has no impact on the temperature-sensitive (biological) wastewater treatment processes (especially nitrogen removal).

However, to make better use of the available (thermal) energy potentials, it is now intended to utilize the excess heat from the combined heat and power unit (high temperature) and heat recovery from the effluent of the WWTP (low temperature), to operate a district heating network for supplying the essential parts of “Wallern an der Trattnach” and “Bad Schallerbach”. This would also help substitute fossil heat sources in the area and generate an economic benefit for the wastewater utility. Overall, the idea is to tap the so far unused energy available at the WWTP, and to evaluate the coupling of wastewater infrastructure and heat supply in the case study area. As the emphasis of the case study evaluations is on energy provision by means of ST, PV, and wastewater heat recovery, relevant infrastructures and technologies are the district heating network, the electricity grid, as well as the heat pumps (and heat exchangers) at the WWTP’s effluent. In order to make use of the recovered heat from the WWTP, district heating is required. Hence, the modelling of a district heating network was carried out in detail for the case study area and is described below.

District heating planning: Starting point for modelling a district heating network are heat demand densities, indicating thermal hotspots in the research area. Then, the heat demand on the building level is calculated. Once the heat demand is determined, a potential network is computed along public roads and paths, derived from the Austrian Graph Integration Platform [41]. In the next step, every single building is connected to the main segments (at a 90° angle) of the district heating network. In the interest of an economically feasible network, it is important to confine energy zones with comparably high heat demand. According to Nussbaumer et al. [42], a minimum connection density of

0.7 MWh/m.a is required for a district heating network to be viable. Hence, for determining these viable supply areas in the form of energy zones, the following criteria are considered:

- Raster cells and individual buildings with high heat demand (e.g., village centres or multi-storey buildings), to guarantee high heat demand per metre of district heating network.
- Buildings owned or managed by the municipalities should be included in the energy zones, as municipalities can act as “initial seedbeds in transition” [43] (p. 22).
- Relevant planning documents such as local development concepts or zoning plans in order to better locate and include future developments or potential heat consumers.
- Natural (e.g., water bodies or slopes) and anthropogenic barriers (e.g., railway tracks), since they limit the realisation of district heating networks.
- Other existing infrastructure (e.g., gas network) and administrative boundaries such as municipal borders, influencing the direction and expansion of the district heating network.

3. Results

The results section is split into two parts, starting with the coupling of wastewater infrastructure and thermal energy supply (Section 3.1). First, the potentials of utilising excess energy from WWTPs via district heating to supply relevant sectors of heat demand are identified. As this excess energy originates from a central RES, it is understood as a local but central supply solution. Concurrently, this allows a first spatial analysis concerning energy hotspots and associated infrastructure planning. The second Section 3.2 includes decentral renewable energy potentials provided by building integrated PV and ST. In addition to heat, electricity is also considered, allowing a more holistic review of SC and the potentials of STM for SC. The STM is applied for both central and decentral RES.

3.1. Coupling Wastewater Infrastructure with Thermal Energy Supply

This section includes heat recovery potentials from the WWTP and the operation of a district heating network, in order to supply the study area with thermal energy. Raster-specific ED were taken as a basis, in order to locate hotspots of heat demand in the vicinity of the treatment plant. By intersecting a digital terrain model and a digital surface model with the underlying building footprints, the building density was calculated. The overlay of the heat demand densities with the building densities shows the suitability for district heating supply along the valley (Figure 6). These results allowed an evaluation on where to focus district heating planning.

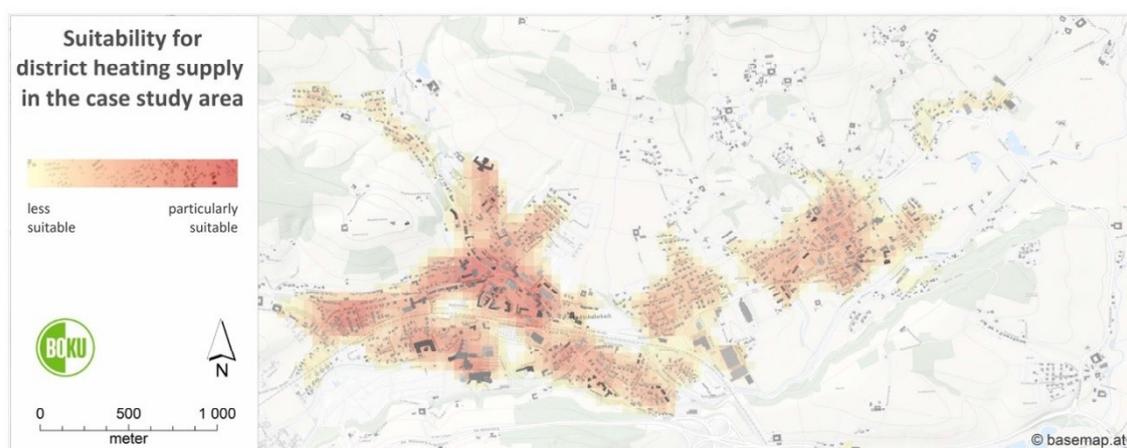


Figure 6. Visualisation of the suitability for district heating supply in both case study municipalities (own illustration).

Concerning the spatial resolution, the heat demand on the building level further offers the possibility to model a concrete district heating network. Residential and municipal

energy demand was calculated, as described in Section 2.2. However, due to the lack of available data on the building level concerning the ED of services, industry, agriculture, and forestry, the raster-specific demand values were disaggregated to individual buildings.

The final district heating network was computed along the road network, connecting all relevant objects of heat demand. As a result, a total of 15 relevant energy zones suitable for district heating supply were distinguished, from which four were neglected, due to comparably low connection densities. As visualised in Figure 7, four energy zones (V1, V2, V3, and V4) serve as links between the larger zones B1, B2a, B2b, B3, B4, W1, and W2. In order to guarantee the usefulness of the results, the degree of connected buildings was reduced. Hence, buildings with a construction period later than 2000 were excluded because of the low energy demand, due to high building standards. Additionally, renovation activities were assumed, decreasing space heating demand of all residential buildings by 20%. The final compilation of energy zones (see Figure 7) covered a total area of 78 ha. The district heating network stretched across 17,400 m, connecting a total of 369 individual buildings. Approximately 20,300 MWh/a of heat demand was calculated, resulting in a connection density of 1.17 MWh/m.a, respectively, in an average heat demand density of 260 MWh/ha.a. The latter varied substantially between the compact settlement structures of “Bad Schallerbach” in the western part of the case study area and the settlement structures of “Wallern”, with a moderate building density in the eastern part of the research area. The WWTP is situated in the eastern part of the area (see Figure 7).

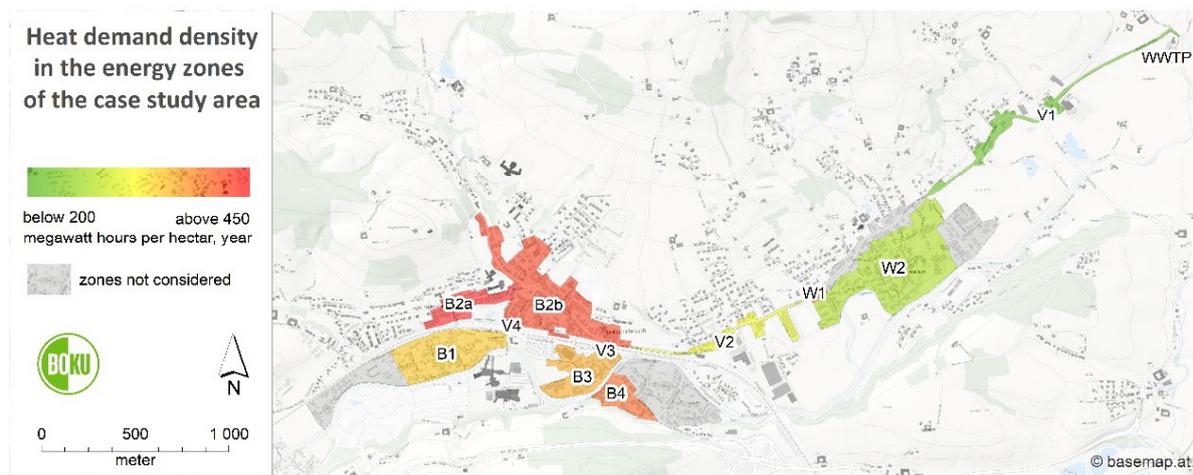


Figure 7. Visualisation of the heat demand density in the relevant energy zones of the case study municipalities (own illustration).

The spatial analyses showed that a heat supply of the case study area, via district heating is a feasible option and that a coupling of wastewater infrastructure with thermal energy supply is generally possible. In order to specify the match between heat supply and demand, the temporal component of central heat supply was further elaborated. Figure 8 shows the temporal variability (diurnal values) of the heat demand in the respective energy zones and the daily thermal heat recovery from the WWTP, applying a cooling of the effluent of 2 K. Hereby, calculations were based on daily average dry weather flow rates, except for rain weather days, where the minimum monthly average flow rates were taken [44]. Using these assumptions, the annual recovered thermal energy from the WWTP was estimated to be 13,600 MWh. In addition to the results of 2 K cooling (visualisation of daily heat recovery based on 2 K cooling in Figure 8), the daily average wastewater flow and wastewater temperature were further used to calculate heat recovery potentials of 1 K, 3 K, 4 K and 5 K cooling, resulting in a total heat recovery of 6800 MWh (1 K), 20,400 MWh (3 K), 27,200 MWh (4 K) and in 34,000 MWh (5 K).

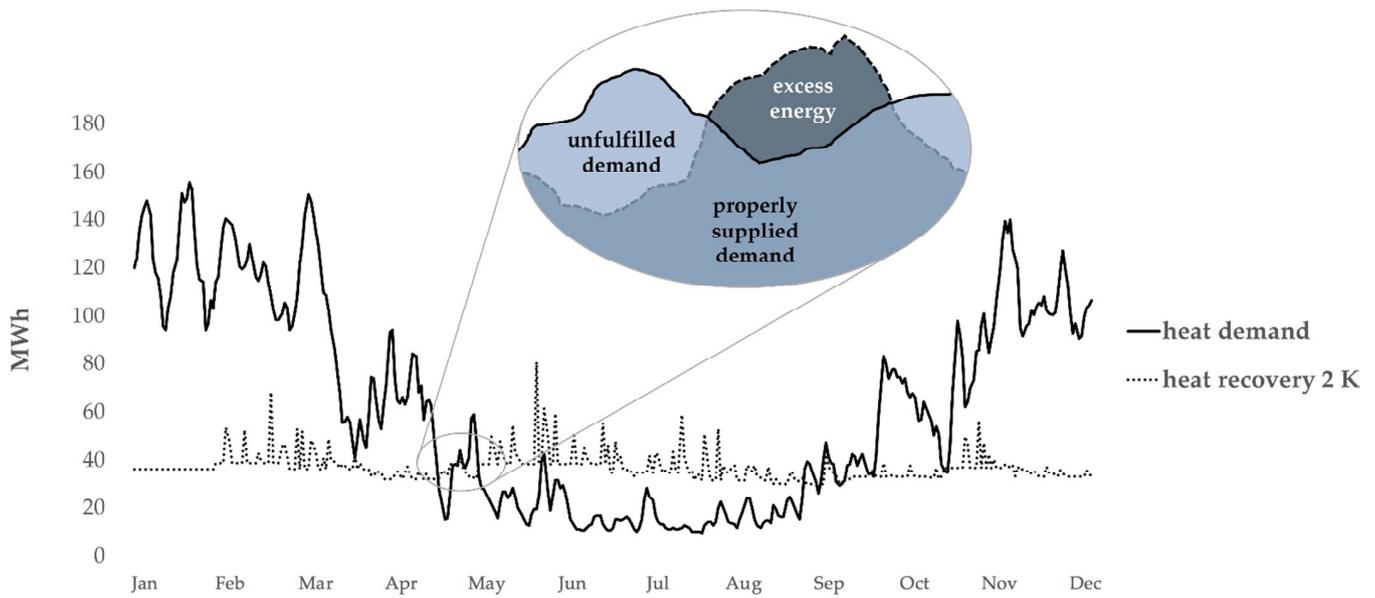


Figure 8. Daily heat demand in the proposed energy zones of the study area and heat recovery from the WWTP in 2016 (own illustration).

The results obtained were further prepared in accordance with the spatiotemporal indicators—Total Properly Supplied demand [TPrSu_{th}], Total Excess energy [TExc_{th}] and Total Unfulfilled Demand [TUD_{th}] of the STM. These indicators are visualised in Figure 8 and are described in details in Figure 4. The final comparison of heat provision and heat demand (based on daily values) is visualised in Figure 9. The figure shows five pairs of bars. The first bar of each pair illustrates energy provision (dashed—properly supplied demand, and filled—excess energy). The second bar represents energy demand (dashed—properly supplied demand, filled—unfulfilled demand). In other words, the sum of properly supplied demand and excess energy represents the total heat recovery, whereas the sum of properly supplied demand and unfulfilled demand accounts for the total heat demand in the respective energy zones.

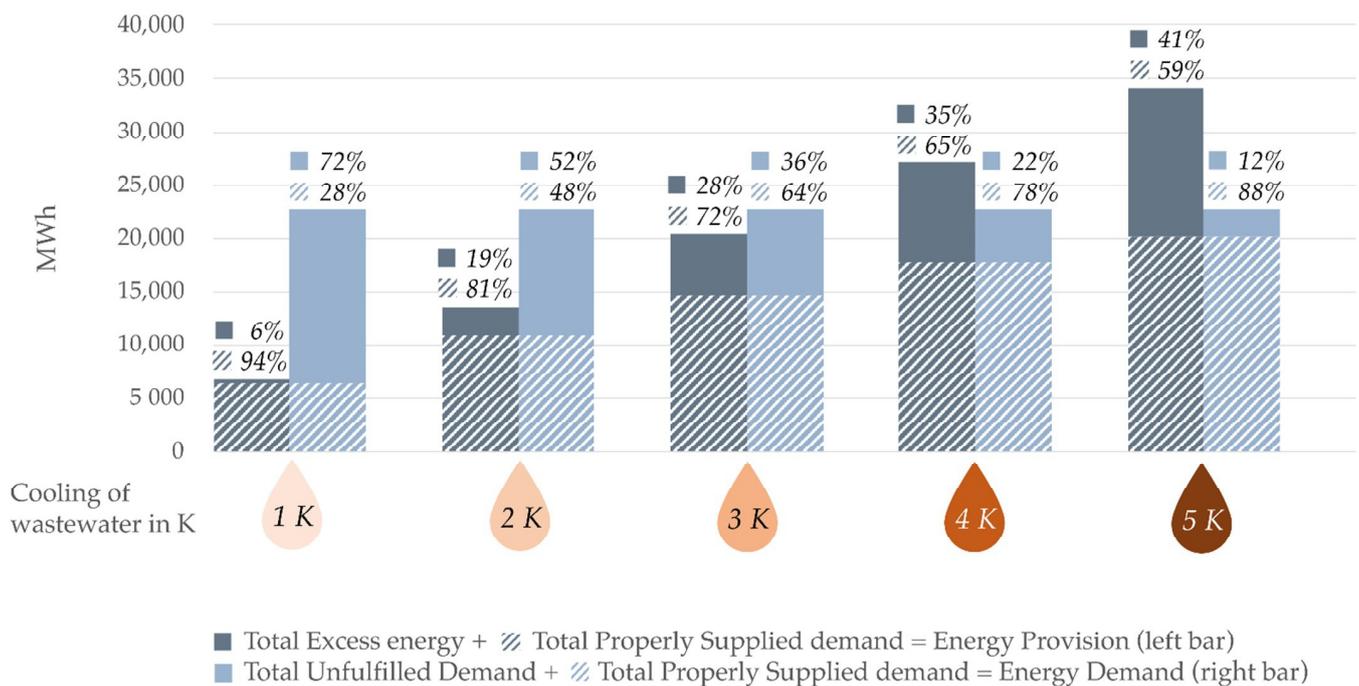


Figure 9. Spatiotemporal results of heat demand in the energy zones and heat recovery from the WWTP (own illustration).

The results showed that the annual heat recovery surpassed heat demand with a cooling of 4 K. Taking a closer look at energy provision (first bars), the properly supplied demand reached 94%, starting with 1 K and continued to decrease to 59%, with a cooling of 5 K. On the contrary, excess heat was lowest at 1 K cooling (6%) and increased up to 41% with 5 K cooling. A significant decrease of properly supplied demand of 13% was observed between 1 K and 2 K cooling, compared to the lowest decrease of 6 percentage points from 4 K to 5 K.

In comparison, the demand side revealed 28% properly supplied demand at 1 K cooling and up to 88% at 5 K cooling. Analogously, total unfulfilled demand decreased from 72% at 1 K cooling to 12% at 5 K cooling. Finally, a sharp increase of properly supplied demand of 20 percentage points from 1 K to 2 K was recorded as compared to only 10% increase between 4 K and 5 K cooling.

This first evaluation of central renewable energy supply can be extended with another SC option—decentral energy provision via solar energy. This allows for instance clarifications on where to focus on central energy provision via district heating and where decentral solutions might be more feasible.

3.2. Coupling of Decentral Energy Supply Solutions

For both case study municipalities, the results obtained from the applied spatiotemporal model, using PV and ST as decentral RES, are presented in this section. Using hourly values, the preparation of the results was carried out for 250-m raster cells and followed the spatiotemporal indicators. The sum of all evaluated raster cells corresponded to the entire municipality. The first pair in Figure 10 illustrates 20% (1/5) roof-top coverage, with either PV or ST. The second pair, 40% (2/5), the third 60% (3/5), the fourth 80% (4/5), and finally the last pair of bars shows good results whenever all roof-top areas (5/5) were equipped with either PV or ST.

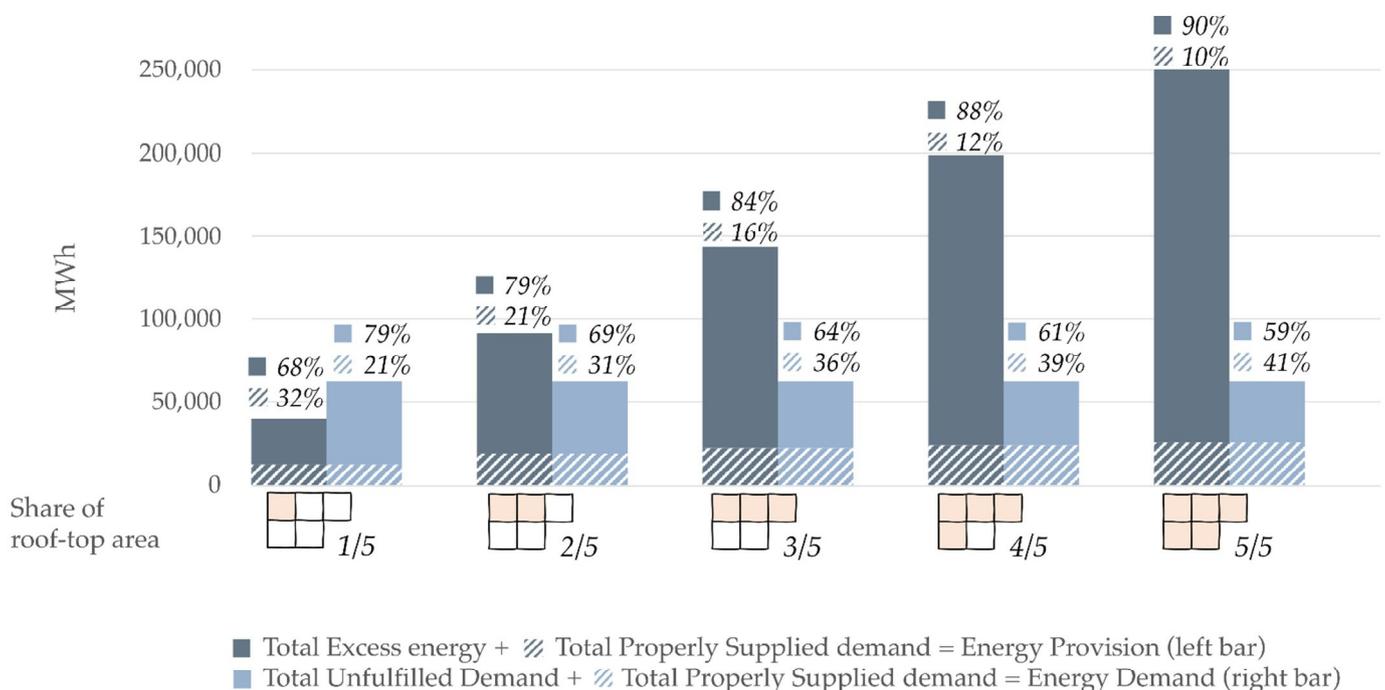


Figure 10. Spatiotemporal results of heat demand and solar thermal energy provision in the entire case study area (own illustration).

The results presented in Figure 10 show that thermal energy provision exceeded the heat demand, starting with a 2/5 roof top coverage. In the context of ST provision, at 1/5 roof-top coverage, almost one-third (32%) of the available solar thermal energy could

be used to properly supply the demand. The properly supplied demand continued to decrease to 10% at 5/5 roof coverage. Excess energy started with 68% at 1/5 roof coverage and rose to 90% if all rooftops were equipped with ST. A strong decrease of properly supplied demand of 11 percentage points from 1/5 roof coverage to 2/5 roof coverage could be observed, whereas properly supplied demand only decreased by 2% from 4/5 to 5/5 roof coverage.

In comparison, at the demand side, the properly supplied demand started with 21% at 1/5 roof coverage and increased up to 41% if all rooftops were covered with ST. Further, the total unfulfilled demand started with 79% at 1/5 roof coverage and decreased to 59% at 5/5 roof coverage. Finally, the highest increase of properly supplied demand was observed from 1/5 roof coverage to 2/5 roof coverage (10%) and the lowest increase was from 4/5 roof coverage to 5/5 roof coverage (2%). Analogously, the decrease in unfulfilled demand was highest from 1/5 to 2/5 roof coverage (79% to 69%), as compared to 4/5 to 5/5 roof coverage (61% to 59%).

A different picture was revealed for electricity (Figure 11), where provision surpassed demand only with a roof coverage of 5/5. Taking a closer look at electricity provision, properly supplied demand started with 70% at 1/5 roof coverage and continued to decrease down to 34% with 5/5 roof coverage. If only 1/5 of rooftops were covered with PV, 30% of excess energy was observed. This value increased up to 66% at 5/5 roof coverage. Significant decrease of properly supplied demand was observed from 1/5 to 2/5 roof coverage (12%), as compared to the lowest decrease of 6 percentage points from 4/5 to 5/5 roof coverage.

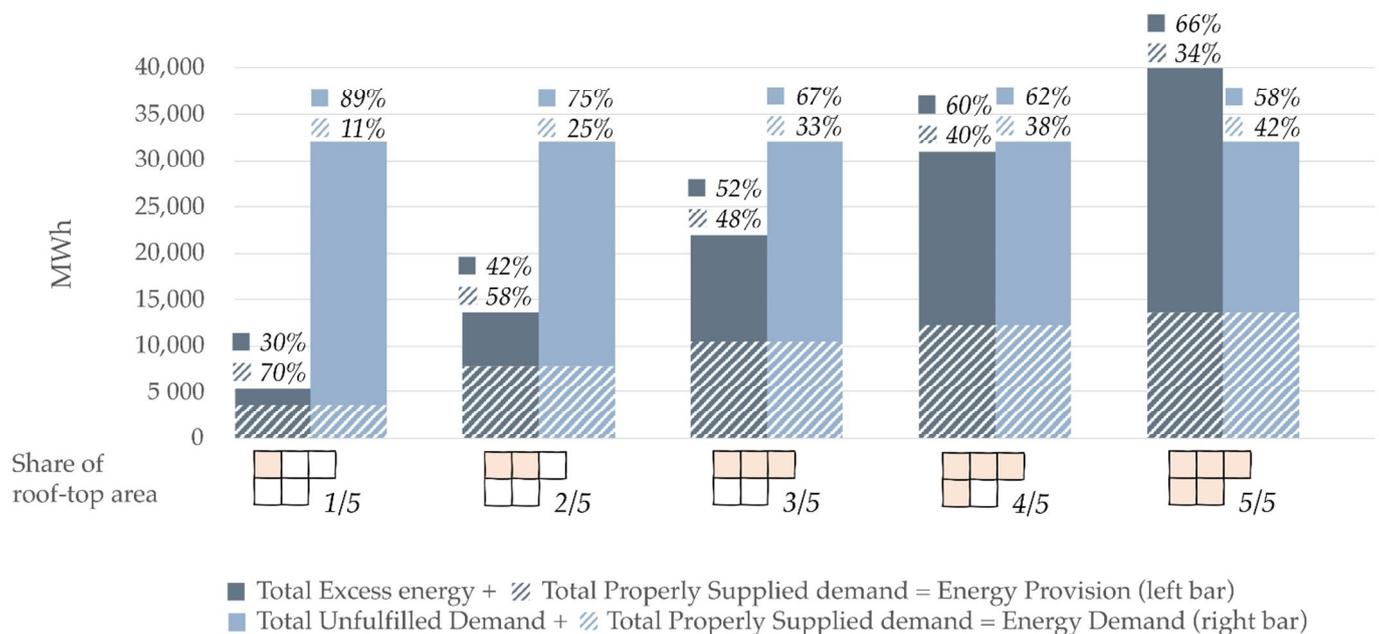


Figure 11. Spatiotemporal results of electricity demand and energy provision via photovoltaic systems, in the entire case study area (own illustration).

Simultaneously, properly supplied demand on the demand side started at 11% (1/5 roof coverage) and increased up to 42% (5/5 roof coverage). Analogously, total unfulfilled demand decreased from 89% to 58%. Finally, a sharp increase of properly supplied demand of 14 percentage points from 1/5 to 2/5 roof coverage was recorded, as compared to only 4% increase between 4/5 and 5/5 roof coverage.

The spatiotemporal evaluations revealed different results for thermal energy and electricity but also for different rooftop coverage. The indicators and the differentiation of rooftop coverage allows a comparison between ST and PV supply in the research area. With the help of the results presented, strategies on where to focus on either central or

decentral energy supply could be derived, finally allowing a more precise discussion on spatiotemporal interdependencies and strategies for SC.

4. Discussion

This section starts with a discussion on the case study results and the corresponding sector coupling implications (Section 4.1). Further, the relevance of spatial planning for sector coupling is discussed and relevant strategies are elaborated (Section 4.2). Finally, the demonstration of strengths and limits of the spatiotemporal model for sector coupling (Section 4.3) are highlighted.

4.1. Spatiotemporal Interdependencies for a Successful Implementation of Sector Coupling

At the beginning of this section, spatial and temporal interdependencies of energy supply solutions in the case study are discussed. The coupling of central (heat recovery from the WWTP) with decentral energy supply (building integrated solar energy) is hereinafter defined as first-level coupling. In contrast, second-level coupling is interpreted as interlinking supply technologies within either central or decentral RES. In the case study, the second-level coupling focuses on building integrated PV and ST.

First-level coupling is displayed with a hierarchical approach in the case study area, departing with grid-bound central renewable energy supply, via district heating. In terms of heat supply, district heating comprises many advantages and (future) potentials for the energy transition [45,46]. Besides recognisable advantages, available and so far untapped heat from the WWTP, between 6800 MWh/a (1 K cooling) and 34,000 MWh/a (5 K cooling), plays an important role and explains why central EP_{th} via district heating is chosen as a starting point for SC. A comparison of daily excess energy from the WWTP with ED_{th} in the supply area reveals properly supplied demand values between 28% and 88% of total heat demand. Hence, recovered heat from the WWTP is capable of providing a constant base load that can be complemented, for instance, via solar energy or decentral heat pumps. Thermal energy provision in the case study via heat recovery is almost entirely renewable. The European Parliament recognises ambient energy from sewage water as renewable energy [38], and the electricity for operating the heat pumps could be provided on site via the combined heat and power unit, and/or obtained from renewable electricity via the grid. In comparison, 53% in Austria [47] and almost 75% of energy input for district heating in the European Union [48] is based on fossil energy. Another aspect is the temperature range that could be provided for district heating. Thus far, it is common practice at WWTPs to use the available digester gas (biogas) to cover internal heat demand (mainly for sludge/digester heating). However, this high-temperature heat might alternatively be used for district heating, more specifically to fulfill temperature requirements, in order to avoid the risk of legionellae growth (see [49]). In turn, the required low-temperature heating for the digestion towers could be provided from the heat pumps.

A closer look at the spatial evaluations in the case study area revealed that an economically suitable district heat supply (calculated connection density of 1.17 MWh/m.a) is only possible in the evaluated energy zones representing the central areas of both municipalities, with high heat demand densities. Therefore, the combination of renewable heat supply via district heating and the potential to substitute fossil energy in these areas of high heat demand would double the benefits towards energy transition. This supports the chosen hierarchical approach used in this study, by starting with locally available RES from the WWTP. A comparison with another central renewable energy source was not carried out in the case study evaluation. The main reason for concentrating only on heat recovery from the WWTP are the large shares of EP_{th} that could be recovered (depending on the cooling, up to 34,000 MWh/a), surpassing the annual ED_{th} in the energy zones of 20,300 MWh/a.

Second-level coupling was executed for decentral energy supply via PV and ST. A detailed comparison of hourly demand and supply in the case study area revealed that EP_{th} exceeded ED_{th} equipping 2/5 of the available rooftops with ST. On the contrary, EP_{el} surpassed ED_{el} slightly above 4/5 rooftop coverage with PV. In terms of self-supply, the

spatiotemporal indicators revealed that the highest increase of properly supplied demand (both thermal and electric) was from 1/5 to 2/5 rooftop coverage. It was suggested to utilise 1/5 to 2/5 ST coverage and 2/5 to 4/5 PV coverage, if surplus electricity could be used for Power-to-X solutions. As excess energy due to high shares of either PV or ST requires additional load shifts, storage systems or regional exchange via grids. Due to the low penetration rates of RES in the past, fluctuating energy supply is not a problematic issue. However, continuous utilisation of RES, especially the more extensive use of Power-to-X solutions, involves new challenges, as higher peaks and frequent fluctuation in energy supply could be expected. In this context, sector coupling offers solutions, as it can be used as a balancing lever in the energy system (e.g., the use of excess electricity in the mobility sector). Another example in this context is the consideration of excess heat from ST to feed energy grids. Simultaneously, heat cascades could also be taken into account. In this context, the potentials of prosumers (producing and consuming energy), as elaborated in Lichtenegger et al. [50] for district heating, likely plays an increasing role in the future of heat supply.

From the spatiotemporal perspective, it is also not advisable to equip high shares of rooftops in the evaluated energy zones with ST to generate thermal energy, since district heating is the preferred option there. Likewise, other decentral technologies of power-to-heat at consumer-sites are not advisable in these energy zones. The focus within the energy zones should be on PV applications to cover ED_{el} . Further, multi-functional areas are mostly located around the centre of municipalities. These areas cover different demand sectors, especially those of the residential and service sector. A diverse set of diurnal $ED_{th,el}$ fluctuations concurrently reveal high shares of properly supplied demand, as this is the case in multi-functional areas. Evaluations in this study additionally showed that these central areas also comprise high heat demand densities. On the contrary, residential areas represent rather constant diurnal demand profiles. In the industrial and commercial sector, ED can vary significantly, depending on the branch or industry segment. In terms of SC, it is advisable to locate different sectors of energy demand (especially for thermal energy) in close spatial proximity, in order to integrate different demand profiles in smaller portions of a grid. Subsequently, the properly supplied demand would ultimately increase, resulting in a more efficient energy system.

The mobility sector could benefit from the generated excess energy. Schäfer et al. [20] highlight the WWTP as an energy hub for the mobility sector, in which they distinguish the use of surplus energy from the treatment plant, for the direct use of electricity for e-mobility, for operating fuel-cell vehicles, or simply for combustion engines using renewable fuels. These alternative utilisation paths could be summarised as power-to-mobility. In the same way, surplus electricity from PV in the case study area can be used for power-to-mobility. Specifically, registered battery electric cars in Europe increased from 734 in 2010 to 341,267 in 2019 [51]. Additionally, the utilisation of electricity for heating and cooling (e.g., [52,53]), Power-to-Gas (e.g., [54]) or simply power-to-X are options for exploiting surplus electricity from RES.

Finally, the importance of energy storage needs to be addressed. Power-to-X is an appropriate approach for storing fluctuating surplus electricity. However, excess heat also requires storage, whenever a surplus is available. Pumped thermal energy storage, as described in Steinmann et al. [55], is an innovative technology to store both heat and electricity. They specifically highlight the benefits of this technology for sector coupling of heat and electricity. Additionally, thermal energy storage systems connected to district heating grids are possible [56].

4.2. Strategies for Sector Coupling in the Context of Integrated Spatial and Energy Planning

As the results of this study revealed, spatial and temporal interdependencies of ED and EP are important factors for a successful implementation of SC. Hence, this second part of the discussion continues with evaluating strategies towards SC. More specifically and in the context of ISEP, hierarchical coupling of central and decentral energy solutions,

strategical benefits of the spatiotemporal indicators, and implications for spatial planning are discussed. The fields of actions and principles of ISEP [11] were used as a basis to deduct the following strategies:

- To support SC, the principle of focusing on multi-functional, appropriately dense, and compact spatial structures is imperative. These energy efficient spatial structures allow high shares of properly supplied demand, due to different functions comprising different sectors of ED. This was shown with the help of energy zones in this research. Simultaneously, the utilisation of excess energy is easier in these spatial structures. Taking the mobility sector as an example, high ED_{el} for charging electric vehicle are seen in areas comprising a mix of different sectors, such as the residential and service/industrial sector. The possibility to charge vehicles at home and at work in the same area offers the opportunity for high shares of properly supplied demand.
- SC-priorities should be considered in ISEP, as energy zones with appropriate dense and compact structures and high heat demand are, for instance, preferred for central solutions like district heating, whereas areas with less heat demand could benefit from decentral supply solutions. First-level (between central and decentral RES) and second-level coupling (e.g., between PV and ST) are to be pursued, if it supports the efficiency of the energy system, since energy efficiency is the central goal of SC.
- The specific use of STM for SC supports an appropriate use of RES. Using STM allows the generation of detailed results in an early stage of planning. Appropriate shares of RES use can be revealed and the emphasis can be put on those areas with high properly supplied demand. Within the framework of spatiotemporal evaluations of $ED_{th,el}$ and $EP_{th,el}$, infrastructure planning, including grid analysis and storage determinations, is also a key aspect.
- A hierarchical evaluation of locally available RES is suggested for SC. In this context, already available and still untapped RES should be given priority.
- The following strategies apply for the spatiotemporal indicators. The focus of ISEP should be on utilising high shares of properly supplied demand. In addition, spatial structures that make use of excess energy (e.g., from nearby settlements) need to be identified. Finally, potential unfulfilled demand should be covered by local available RES.
- Future spatial developments need to include the question on where efficient SC is possible. The designation of priority zones for SC need be included in spatial plans, as this is already partly realized for district heating (e.g., [57]).

As was shown, the principles were matched with specific ideas of SC and the principles of ISEP already included many ideas of SC. Integrating SC as a part of spatial planning would offer more opportunities for reframing planning priorities, for increasing the precision of planning, and for steering strategic spatial planning towards the energy turn.

4.3. Strengths and Limits of Spatiotemporal Modelling for Sector Coupling

The strengths and limits of the applied STM are elaborated in this chapter, including the relevance and shortcomings of the methodology for SC. An essential strength of the model is its simplicity of using only two annual input values ($ED_{th,el}$ and $EP_{th,el}$), in order to derive three output indicators in high temporal resolution—properly supplied demand ($TPrSu_{th,el}$), unfulfilled demand ($TUD_{th,el}$) and excess energy ($TExc_{th,el}$). In a step-by-step approach, the properly supplied demand shows whether a preferable energy source is sufficient enough to supply certain sectoral demands. Potential unfulfilled demand must consequently be met by another energy source that could potentially be provided via excess energy from a different central or decentral energy source. In this context, the spatial and temporal interconnections play a vital role. For instance, excess energy generated in one settlement on private buildings could be used in another settlement or in the same settlement for another demand sector. From the perspective of SC, these comparisons are essential in order to show strategic paths on how to increase energy efficiency and renewable energy supply. Additionally, the approach of not specifically addressing only

one technology, allows an adaptation or extension of the model with any $EP_{th,el}$ technology and/or $ED_{th,el}$ sector, making it a useful tool for SC. Specifically, the temporal variability of renewable EP and diurnal fluctuation of energy demand require planning in high temporal resolution. Hence, hourly demand and provision time-series allow useful comparison of both $ED_{th,el}$ and $EP_{th,el}$. Depending on the intended level of detail, high temporal resolution also offers the opportunity to aggregate time-series to diurnal, monthly, or annual values. Likewise, the spatial dimension of the model also offers the opportunity to aggregate from individual buildings to settlements, statistical units like raster cells, or to entire municipalities. This spatiotemporal flexibility is another strength of the model. Solar energy provision for instance, even allows an evaluation beyond the building level, as the rooftop areas represent the highest spatial resolution. In this context, the variation of 20% steps of rooftop coverage offers even further technology-specific variations, which could be seen analogously to the variations in the cooling of the effluent from the WWTP. Using these variations, both first-level (between central and decentral RES) and second-level coupling (e.g., between PV and ST) could be addressed in a simple manner. Finally, added value of the applied STM is seen for strategic spatial planning in the context of ISEP [11]. On the one hand, the spatiotemporal accuracy of the results allows a more precise planning via strategic planning instruments, such as regional and municipal spatial development strategies. On the other hand, at an early stage of the planning process, the same accuracy reveals its strengths by allowing planners and decision-makers a more precise view on the planning scheme, before a detailed and often more expensive project planning is required.

In terms of limitations and from the perspective of optimizing the model, energy storage systems to compensate fluctuations or the use of electricity for heating (e.g., [24]), were not included in the methodology, as technology-specific optimisations were not the scope of the research. Similarly, technology-specific parameters of EP (derived for solar energy from [18,35]) were kept constant. A variation of efficiency parameters for PV, ST or heat recovery would show additional bandwidths of EP potentials. Further, the quality of the input data can vary, depending on the time of data extraction of the building footprint, for instance, which were used as the basis for modelling the rooftop areas. Hence, some settlements might include higher solar energy potentials than others, depending on the accuracy and the recency of the available building footprint. Although the model offers the opportunity to distinguish between the share of rooftop areas, a classification of rooftop areas in accordance to their capability of energy generation was not followed. In general, increasing the temporal resolution within the STM would further significantly increase data processing efforts, making it more difficult for a broad application. Due to confidentiality, data from raster cells that are insufficiently populated is restrained [58]. Therefore, some ED that would actually be present could not be considered in the final results. Finally, it should be mentioned that the generated results do not substitute detailed energy planning. However, the high spatiotemporal resolution and the flexibility of the model allows to generate more precise results for ISEP, which should be continuously addressed in future research. The presented limitations do not diminish the relevance or suitability of the methodology for SC. On the contrary, the straightforward approach of the model and the spatial and temporal flexibility allow the coupling of various renewable energy supply solutions, with a different set of spatially differentiated sectors of energy demand. Further, SC is not only relevant at the building level or at the national level. An evaluation of SC solution on different spatial levels, as applicable in the presented spatiotemporal model, allows a differentiation between different SC strategies.

5. Conclusions

The European Commission recently described sector coupling as Energy System Integration [1]. However, a universally valid definition of SC is still in process. The present findings of the research contribute to the ongoing debate about SC from a spatiotemporal point of view. After applying a STM on the local scale, the results reveal a wide variety of uses for SC, such as realising the coupling of different central and decentral RES, optimising

grid-bound energy supply solutions, or identifying spatial structures most suitable for SC. For a successful implementation of SC, spatial analyses in an early stage of planning are required. In this context, the evaluated spatiotemporal indicators can be strategically used for the implementation of SC. High shares of properly supplied demand and low shares of unfulfilled demand indicate an efficient energy system, whereas renewable excess energy can be used for other demand sectors. The applied indicators in this study are well-suited to elaborate meaningful pathways for the successful implementation of SC, also in other spatial contexts.

Additionally, it was shown that locally available RES are capable of supplying high shares of ED in different demand sectors. This stands in particular for the fact that the energy transition could be achieved at the local level, but should be complemented by a regional balance of supply and demand, taking spatial and temporal patterns into account. Further, the specific approach of this study could be replicated by using different kinds of RES for both heating and electricity. With respect to heating, other heat recovery sources (e.g., from industrial processes) or building integrated heat pumps are examples that can be used. For instance, wind power or hydropower can be used for renewable electricity provision. Other interesting technologies for SC, such as combined heat and power plants or photovoltaic-thermal collectors providing both heat and electricity are also important to mention in this context. Additionally, a variation of different energy demand sectors and corresponding infrastructure that were not specifically addressed in this research could be used with the presented approach in this study. Further research addressing both SC and the decarbonisation of the energy system (like [59]) is required. However, by including the spatial and temporal dimensions, novel solutions can be elaborated specifically for strategic energy system planning, integrated spatial and energy planning and, depending on the spatial structures, for the successful realisation of SC. Finally, further research is suggested to be carried out for different spatial archetypes. This would be particularly interesting for decision-makers and for strategic spatial planning, as the application of a complex spatiotemporal model is time-consuming, needs proficient computing power and expertise, and is, therefore, hardly suitable for planning practice.

In the context of the energy transition, SC also needs to be seen along with other pioneering concepts and developments, such as recently advanced energy communities [60], smart cities [61] or circular cities [62]. These concepts have certain similarities as they are currently being implemented. Therefore, it would make sense to use synergies and, above all, consider such concepts in strategic spatial planning, in order to advance the energy transition.

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