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# Integrating Energy Demand and Local Renewable Energy Sources in Smart Urban Development Zones: New Options for Climate-Friendly Resilient Urban Planning

Franz Zach <sup>1</sup>, Florian Kretschmer <sup>2,\*</sup>  and Gernot Stoeglehner <sup>3</sup> 

<sup>1</sup> Austrian Energy Agency, Mariahilfer Strasse 136, 1150 Wien, Austria; franz.zach@energyagency.at

<sup>2</sup> Institute of Sanitary Engineering and Water Pollution Control, University of Natural Resources and Life Sciences, Muthgasse 18, 1190 Wien, Austria

<sup>3</sup> Institute of Spatial Planning, Environmental Planning and Land Rearrangement, University of Natural Resources and Life Sciences, Peter-Jordan-Strasse 82, 1190 Wien, Austria; gernot.stoeglehner@boku.ac.at

\* Correspondence: florian.kretschmer@boku.ac.at; Tel.: +43-1-47654-81115

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**Abstract:** In recent years, most cities have experienced rapid population growth. Concurrently, international policies have called for substantial reductions of greenhouse gas emissions. Additionally, the resilience of energy-supply systems has become more important. Consequently, solutions to exhaust locally-available sources must be developed to minimize the fraction of fossil fuels for heating, cooling and electricity. This article shows an example of designing a low-temperature heating and cooling grid based on locally-available renewables and waste heat and introduces general hypotheses concerning smart energy planning in urban development zones. Taking an urban development area in Vienna, Austria, as example, it is shown that wastewater, geothermal and (office) waste heat, solar energy, and the heat content of ambient air can play an important role within a climate-friendly urban energy concept and that heating and cooling demand can be covered completely on-site. From an environmental point of view, the concept is promising, as greenhouse gas emissions and the non-renewable primary energy consumption can be reduced by over 70% compared to conventional gas heating, while, based on current (fossil) energy prices, it is economically not fully competitive. The gap could be closed e.g. by CO<sub>2</sub> taxes on fossil energy sources or (temporal) subsidies for renewables. Additionally, reservations of stakeholders in the energy sector against this innovative approach must be dismantled.

**Keywords:** waste heat; low-temperature; heating; cooling; urban development; wastewater; PVT; energy grid

## 1. Introduction

In recent years and decades, cities have experienced population growth, and this trend is estimated to last [1]. In order to use the limited urban areas efficiently, moderate densification of buildings is a broadly discussed option [2–4]. Moreover, within these new quarters it is desirable to mix different building functions (domestic, workplaces, leisure, commercial, etc.) [5]: Moderate densification and mixing building functions lead to benefits in different areas of social, economic and environmental interest, e.g., the land use is minimized, distances between buildings are kept closer (reducing traffic and travel time), and the heat consumption density as well as the annual full load hours for heating are increased. The latter is also of particular importance for the feasibility of heat grids and to a better usability of waste heat which can contribute to reduce fossil fuel consumption. Heating and cooling of

buildings includes hot water, which accounts for 27% of the energy consumption in Austria [6] and 32% in the EU [7]. Electricity and heat production together contribute to 31% of the global greenhouse gas (GHG) emissions [8] and these sectors have a large impact on worldwide environmental pressures and economic aspects. Consequently, not only the reduction of fossil energy use, but also their replacement by renewables deserves high priority in future urban planning. Sector coupling concepts [9,10] aim at integrating energy generation and consumption processes from different sectors such as heating/cooling, electricity, industry, commercial, and transport with the aim of optimizing resilience, reducing energy consumption and GHG emissions, as well as increasing economic benefits. A possible application is e.g., the provision of energy from waste heat from industry or offices to a grid which serves as a heat source for households or the optimization of building typologies for the generation of electricity and heat from solar collectors which can both be integrated in an urban energy concept.

Apart from the above-mentioned densification and functional diversification, another important factor for the design of urban quarters is their energy security or resilience [11,12], where the strength against shocks or crises of an energy system (e.g., blockade of fuel deliveries from other countries, blackouts in the electricity grid, natural hazards, etc.) can be described by the factors diversity, efficiency, exposition, and redundancy. The energy supply system shall be able to deliver the needed energy in as many crises or shock situations as possible. Therefore, different options to foster resilience can be followed: In order to implement diversity and redundancy, different sources shall be used in order to be able to switch the energy mix in case one source falls out, avoiding large distances in order not to be dependent on long transportation pipes for energy sources; energy sources that are available on-site as unlimited as possible reduce exposition to disturbances and moreover increase efficiency.

Merging these aspects, it is desirable to design heating and cooling grids that are supplied by diverse, locally available non-fossil sources. Also, electricity underlies the same principles and should therefore be designed accordingly. In order to enlarge resilience against short-term blackouts, the capacity of the production sites can be increased and/or storages can be built [13]. A variety of technologies exist to provide thermal energy from locally-available sources, e.g., wastewater heat recovery using heat pumps [14,15] or the use of solar energy, where three different technologies exist: Photovoltaics (PV), solar thermal (ST) and hybrid photovoltaic-thermic technology (PVT), from which the latter is a combination of the first two. PVT is currently a less implemented technology compared to PV and ST, but shows advantages especially in surface efficiency and when using a low temperature, the cooling effect on the PV panels is higher, which increases the electricity output [16]. Other important energy sources are ground water heat, geothermal energy, the heat content of ambient (outside) air, and all sorts of waste heat, e.g., from cooling, industrial processes [17] (often used internally) or data centers [18]. In many cases, these are low-temperature sources and, therefore, are also suitable for cooling purposes. Electricity production in densely-built urban areas is typically limited to PV except in cases where the local geothermal circumstances are optimal. Larger wind power plants are not suitable due to the minimum distance requirements to settlements [19], while hydropower can be an option, if the area is attached to a river.

Considering heating and cooling, each source has a specific temperature range, at which thermal energy can be delivered. However, if they feed into one single grid, temperature management has to be implemented. Therefore, heat pumps are an appropriate technology as they can transfer heat between different temperature levels. Grid typologies which deliver heat at ambient temperatures (around 10 to 20 °C)—also called low-temperature grids or anergy grids—have been shown to be successful implementations [20]. Contrary to this approach, conventional heat grids contain centralized heating stations delivering the energy at the temperature level needed [21]. Cooling purposes can be covered by low-temperature grids as well. For an urban development area, a low-temperature grid typology is appropriate in most cases, as the buildings can be designed accordingly (e.g., panel heating instead of radiators). Electricity grids are challenged to store or feed-in temporary surplus energy in order not to waste PV- or PVT-generated electricity [22]. While feeding-in is not an economically attractive option and might temporarily lead to electricity peaks that do not meet the energy demand in many

cases, storing needs extra infrastructure. Therefore, sector coupling and smart grids might offer new technical solutions.

Although there is a wide range of renewable energy sources available at urban levels, today energy supply (especially thermal energy supply) is still largely dominated by fossil energy sources [23]. Therefore, various optimization approaches for district heating systems are documented that aim to reduce primary energy demand and GHG emissions. Building-to-grid models facilitate the simultaneous design of buildings in new quarters and the grid serving for heating (and cooling) purposes [24]. Furthermore, thoughts on ownership structures are given in order to simplify implementation and to avoid user conflicts. The easier incorporation of renewable energy sources in the future is a clear benefit of grid systems compared to local heat generation [25]. Also, load shift opportunities are better and costs can be reduced. Further research demand can be identified concerning the inclusion of relevant stakeholders, the enhancement of the knowledge base, and the introduction of integrated spatial and energy planning approaches in smart urban development. In order to contribute to the methodological development for urban energy system design on the neighborhood scale and to promote more climate-friendly urban planning, this article presents a novel approach that integrates urban planning and energy system design for a resilient, local renewable energy supply with stakeholder involvement from the start of the planning process (Section 2). The proposed methodology is developed and tested in a case study of a 44 ha urban development area in Vienna, Austria, designed to accommodate up to 15,000 inhabitants and 5000 workplaces, embedded in a large park and further green infrastructures. This study investigates options for electric and thermal energy supply, combining different technologies based on renewable and locally-available energy sources. Different supply scenarios are developed and the related energy balances and environmental and economic benefits are evaluated (Section 3). Based on these results, novel hypotheses concerning integrated smart energy planning in urban development zones are being derived and discussed (Section 4). Finally, some conclusions for smart urban development are drawn (Section 5).

## 2. Materials and Methods

In order to address the challenges posed above, a sequence of methods is proposed in a four-step approach that includes: (1) system design—scenario development on behalf of energy balances; (2) environmental and (3) economic evaluations; as well as (4) the presentation of results to decision makers and stakeholders including a discussion. Following a general overview on the project framework (of the case study), the five single steps are now being presented in more detail.

### 2.1. Project Framework

The project consortium involved four different partners of different expertise and responsibility: (1) the Austrian Energy Agency as the home institution of the first author of this article was in charge of project management, stakeholder coordination, demand calculation, supply system design, and economic and environmental evaluation; (2) a research institution specializing in solar energy use and interaction with storage; (3) a heat pump manufacturer took responsibility for heat pump dimensioning; and (4) an engineering office for geothermal storage dimensioning.

The project consortium already had a rather interdisciplinary character. However, for the implementation of a large-scale heating and cooling system, the involvement and expertise of additional stakeholders was considered imperative. A multi-perspective setting of the project framework should guarantee the development of viable and well-accepted solutions.

During the planning process for designing the energy system in the designated development area, stakeholder involvement was implemented [26] by means of an advisory board that included the main stakeholders suitable for the early stage of the planning process: Representatives from the department of energy planning of the City of Vienna (MA 20 together with the Agency Urban Innovation Vienna), Vienna energy supply (Wien Energie), Vienna sewer operation (Wien Kanal), and the Geological Survey of Austria (Geologische Bundesanstalt, GBA) were involved (Table 1). Their expertise was especially

essential in defining the assumptions regarding building data and the design of the grid and storage system and to reflect the obtained results. They were consulted in about 2-month intervals (workshops), and after finalization of the study, a detailed presentation of the results with a discussion and feedback round took place.

**Table 1.** Advisory board organizations and functions in the project.

Organization	Expertise
City of Vienna—department of energy planning Agency Urban Innovation Vienna	future building and energy technology developments in Vienna
Vienna energy supply	defining consumption profiles and buildings technology
Vienna sewer operator	wastewater heat recovery
Geological Survey of Austria	geothermal storages

An overview on the topics and the main results of the different workshops can be seen in Table 2.

**Table 2.** Workshop structure with the Advisory board throughout the project.

Workshop No.	Main Results (Excerpt)
1	Decision on the designated case study area, overview on the status of the planning process, communication of the project structure and timeline
2	Specification of buildings' energy consumption and definition of possible energy sources
3	Discussion of preliminary results (grid planning, raw energy amounts per source), planning of a study tour (Switzerland, Germany), possibilities for storages, specification of usage and consumption profiles
4	Discussion and decision on warm water heat pump options, discussion on cooling energy (external feed-in of waste heat and on-site)
5	Planning of an in-sewer measurement campaign for better defining the wastewater heat potential, specification of technical options for usage
6	Final project presentation and discussion

Additionally, expertise was collected from low-temperature grid operators in Switzerland (e.g., Suurstoffi [20,27], ETH Zurich [28], Richti-Areal [29] and Familienheimgenossenschaft Zürich) during on-site visits of the project consortium.

## 2.2. System Design—Scenario Development

For the scenario development, the following issues have to be addressed:

1. Definition of case study area: The case study area has to be selected, in this case, it is the urban development area “Nordwestbahnhof” (north-western railway station) in Vienna. Here it is important to note that the surrounding urban fabric has to be taken into consideration as important heat sinks and heat sources in the proximity of the new development should be taken into account to optimize energy systems.
2. Definition of potential local energy sources: First, a screening of potentially available heat sources has to be carried out. Second, by consultation of stakeholders, this list of sources might be confined by taking technical, political and institutional considerations and barriers into account.
3. Definition of storage technologies: Analogously to step 2, potentially locally feasible storage technologies have to be selected and discussed with the stakeholders involved.
4. Design of the thermal grid: The location, temperature levels and heat sources have to be considered.



5. Scenario determination: Scenarios are defined based on energy balances and stakeholder discussions after having identified technically-feasible energy provision opportunities.

### 2.2.1. Case Study Area

The research was done at the example of an urban development area in Vienna, Austria named “Nordwestbahnhof” (north-western railway station). The area has a size of about 440,000 m<sup>2</sup> [30] and was previously used as a train station for goods transportation but has now lost its function as a new terminal was built in the south of Vienna. As mentioned in Table 2 (workshop no. 1), the area was selected in a discussion process with representatives from the City of Vienna and Vienna energy supply according to the status of the planning process (building cubatures were defined but no energy supply concept has been elaborated), its large size, and accordingly, the importance of this development area for the whole city.

The local authorities decided to dedicate this area to different functions in the future such as housing, shops, schools, leisure, etc. An overview of the area can be seen in Figure 1. The gross floor areas per function are displayed in Table 3. In order to fulfil the climate goals and to ensure a sustainable and secure energy supply for the new quarter, the project funding organizations (see acknowledgement) aimed at developing concepts regarding the usage of renewables and waste heat, with a focus on locally-available sources.



**Figure 1.** Overview over the intended building positions and types of use at “Nordwestbahnhof” development area, adapted with permission from [31] OEBB (internal document): Vienna, Austria, 2019, including the main sewer at the right (in brown), arrows indicate flow direction.

**Table 3.** Building use in the “Nordwestbahnhof” development area based on Ref. [30].

Function	Gross Floor Area (m <sup>2</sup> )
Domestic	494,000
Offices	156,000
Commercial	35,000
Culture, Infrastructure, Schools, Social	73,000
<b>TOTAL</b>	<b>758,000</b>

In principle, a grid with seasonal heat storages can work without additional heat sources if heating and cooling demand are roughly balanced throughout the year. In this case, however, it was clear from the beginning that heating demand would be much larger than cooling demand. Therefore, the search for additional heat sources (apart from waste heat from cooling) was necessary. Still, a cooling demand of 2000 MWh/a in the “Nordwestbahnhof” area was assumed (derived from experience of the stakeholder group from other development areas in Vienna). Moreover, a search for waste heat in the surrounding areas was performed. Both waste heat at Nordwestbahnhof and outside would help to lower the need for heat energy sources.

### 2.2.2. Potential Energy Sources (Heat and Electricity)

In the following, all energy sources available on-site are presented and their potential suitability for the case study is briefly discussed. These are wastewater, solar, waste heat, ambient air, groundwater, and surface water.

The most important factors for the feasibility of wastewater heat recovery [14,15,32,33] are the wastewater flow and temperature, the supply distance, the technical possibility to build a supply network, as well as the permission of the sewer operator and the responsible water authority.

In the local specific context, a main sewer passes the area of “Nordwestbahnhof” in its east/southeast. The catchment area mainly consists of domestic and office buildings. The wastewater treatment plant (WWTP) is located about 10 km away from the urban development area; therefore, the usage of the wastewater before treatment is the only viable option.

For the estimation of the available thermal potential, at the first stage, the wastewater temperature was set equal to the value measured at the WWTP inflow and the flow was estimated by analyzing the catchment area (number of inhabitants, offices were neglected due to lower consumption and to consider a buffer for the energy supply). In a later stage and to learn more about the actual local-specific (dry weather) conditions, the wastewater flow and temperature were measured directly in the (combined) sewer for a period of about 5 months. To exclude wastewater data influenced by wet weather conditions, precipitation data of a nearby rain gauge provided by the Austrian Federal Ministry for Sustainability and Tourism [34] was used.

The fact that new buildings have been erected allows for the adaption of the design of the houses to ensure that the usage of solar energy is possible (leaving areas on the roofs free from terraces, windows, etc.; orientation of the roofs; avoid shading of potential roof areas; etc.). In order to maximize the energy output, the research focused on the most area-efficient technology—in terms of energy generated per m<sup>2</sup> installation—which is the photovoltaic thermal hybrid solar (PVT) collector. As a reference, also the common photovoltaic (PV) collector was considered. Solar energy is the only source which is not only taken into account for heat, but also for electricity supply.

For the output of PV and PVT collectors, and the storage system, a calculation using the program POLYSUN [35] was performed. A balance was calculated taking the desired temperature levels for direct input into the low-temperature grid into account. As Polysun gives a size limit of the simulated system, 1/100 of the size of the system needed for “Nordwestbahnhof” was simulated and rescaled afterwards. Solar energy is the only source in this research also taken into account for electricity generation.

A thorough analysis of the ongoing processes in the surrounding area was performed via analyzing building usage and aerial images indicating large cooling devices on roofs. However, waste heat will only be accessible if there is an economic benefit for the operator as well. Data was difficult to obtain, but a large office building (see Figure 1) was identified, for which an estimation for the annual cooling energy consumption was gained.

It was also considered that this building could have been connected to the low-temperature grid not only for delivering waste heat to the grid, but also to obtain cooling energy from there. However, this opportunity was not further taken into account as stakeholder involvement revealed a lack of interest. Furthermore, its consideration would have caused fundamental changes in the existing cooling system of this building.

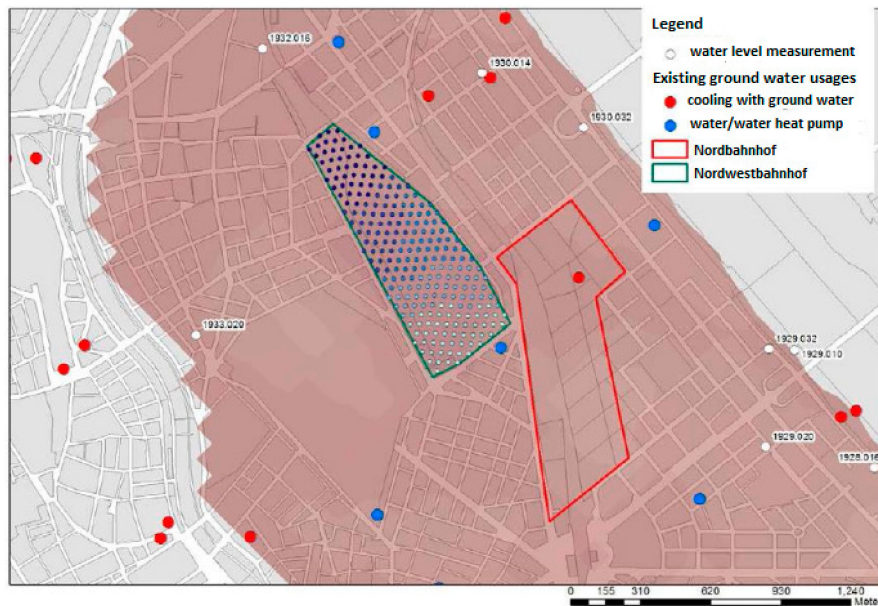
In order to maximize the seasonal performance factor (SPF), air heat pumps shall only run if the outside temperature exceeds a certain limit. In this system design, seasonal heat storages allow such a dimensioning as heat production and consumption do not have to correlate timely.

The threshold of 10 °C outside temperature for the operation of the air heat pumps secures a comparably high annual performance. In Vienna, this value is exceeded at 5000 h per year. Another approach would be to turn air heat pumps on if locally-produced electricity from PV and PVT plants is accessible. However, the available electricity amount is comparably small and, therefore, most of the time the production does not exceed the local consumption so that this option was not followed. As the seasonal heat storage needs to be balanced throughout the year (heat input must equal heat output) and the potential of air as a heat source is comparably high in a 44 ha quarter, ambient air was considered as the heat source that secures the annual balance. Still, there are some limitations: A potential barrier within the stakeholder discussions was also the noise of air heat pumps which is a topic of interest especially in densely-populated areas. Also, use conflicts (roof terraces, PV respectively PVT collectors, etc.) reduce the potential. However, acoustic issues and also the need for placing outside units were not seen as problematic by the involved stakeholders.

Groundwater as a further option to generate thermal energy is a widely-used energy source which is shown by the large number of groundwater plants in the surrounding area (Figure 2). If existing groundwater plants are negatively affected by new ones, the new plant cannot be installed due to legal reasons. Taking into account these restrictions, an analysis of the influence on existing plants was performed.

The analysis of existing plants using ground water showed that a potential of 418 kW is available. As this would be a rather small contribution to the total needed energy amount, ground water was not taken into account.

Two larger rivers are situated in the vicinity of the development area (about 1 km): The Danube with about 1.900 m<sup>3</sup>/s average flow and the Donaukanal with 160 m<sup>3</sup>/s average flow [37]. Both rivers have about the same annual temperature profiles with water temperatures around 5 to 10 °C during the heating season. In discussion with Vienna energy supply and the City of Vienna, it was decided not to take these sources into account as the (supply) distance to the case study site is larger and the river water temperature expected to be lower compared to other on-site heat sources.



**Figure 2.** Existing ground water usages around Nordwestbahnhof, limiting the potential for a large ground water plant at Nordwestbahnhof, reproduced with the permission of [36], produced within the project “Urban PV+geotherm”, Goetzl, G.; Fuchsluger, M. 2016.

### 2.2.3. Storage Technologies

Based on local climatic circumstances, one can expect the energy/heat generation profile to show a peak in summer (mainly due to solar contribution and higher wastewater temperatures) and the consumption profile to show a peak in winter. Therefore, the inclusion of thermal storages appears necessary. The inclusion of seasonal storage means that the cooling demand (predominantly in summer) can serve as waste heat potential to cover at least parts of the heating demand (predominantly in summer) and the heating demand could serve as “waste cool” potential to cover the cooling demand.

There exists a variety of different technologies of which ice storages, water storages and geothermal boreholes were taken into account; others are water basins and chemical storages. Water storages were not chosen as the City of Vienna preferred another option mainly due to the insecurity of storing large water amounts below large buildings. Ice storages have temperatures around 0 °C, therefore, leading to a reduction of the seasonal performance of the heat pumps. Moreover, ice on the heat exchangers can block the heat transfer between storage and grid. As storage space was sufficiently available, this option was not taken into account.

Therefore, the technology finally chosen for the calculations was the construction of geothermal boreholes as it is a comparably cost-effective option, whereas the lower heat density [38] was not considered as a problem. In small applications, geothermal energy can be used as a heat source. However, in the case of large geothermal plants, heat extraction over the years leads to a permanent cooldown of the ground [39]. Therefore, in projects of larger dimension and higher density, geothermal energy can only be considered as a seasonal storage but not as a continuous heat source.

The calculations of the borehole system regarding temperatures and energy flows were done using the program “Earth Energy Designer” [40].

### 2.2.4. Design of the Thermal Grid

The thermal grid needs to serve heating, cooling and warm water purposes. Therefore, the system needs to deliver energy at different temperature levels. Warm water has to be delivered at over 60 °C due to legislation regarding potential legionellae contamination [41]. Heating energy was assumed to be delivered at no more than 40 °C. The design temperature of the grid was set to an outside temperature of minus 12 °C (according to the Austrian standard [42]).



A central thermal grid at temperatures between 8 and 20 °C was proposed, which was attached to five heating stations spread over the development area Nordwestbahnhof, where heat pumps transfer the temperature from the energy grid level to the level needed for heating. For cooling, no heat pumps are needed as the temperature of the grid was dimensioned so that direct cooling could take place. Panel cooling allows higher inlet temperatures for cooling. The dynamics of the low-temperature grid were simulated via Earth Energy Designer (EED).

Considering central heat provision (local heating of warm water was not considered as it would increase the electricity consumption remarkably), there are three possibilities to provide warm water:

1. The heat pumps which deliver heating energy (inlet temperature is dependent on the outside temperature) deliver warm water energy as well. Warm water energy is provided within special timeslots—the inlet temperature is changed and valves are switched from heating to warm water mode.
2. Special warm water heat pumps use the heating buffers as a heat source. This leads to a large range of operational conditions of the warm water heat pumps throughout the year and to a two-step heating of warm water which reduces the performance of the heat pumps.
3. Special warm water heat pumps use the energy grid as a source as well. This is the preferred option as the operational conditions can be kept quite stable and performance is better; therefore, this opportunity was chosen.

#### 2.2.5. Scenario Determination

The following framework conditions and technological options were applied for scenario determination (including a reference scenario) based on the stakeholder involvement described in Section 2.1: (1) Dimensioning heat pump systems to the lowest outside temperature is often avoided mainly due to economic reasons; therefore, a bivalent approach is taken into account, where below 0 °C outside temperature, gas boilers would support the grid. Alternatively, a system was evaluated where no fossil contribution to the heat supply would take place. (2) PVT collectors would lead to an optimal use intensity of the available area, but were by large parts of the stakeholder group seen as questionable regarding their performance, reliability and economic feasibility. Consequently, as an alternative way to use solar energy, the (conventional) PV collector was introduced. Solar thermal collectors were not seen as appropriate as a certain amount of electricity self-supply was required from the authorities. (3) A large potential is ascribed to air heat pumps. Due to space requirements and noise emissions, stakeholders prefer a low amount of air heat pumps. However, stakeholders and the project team agreed that the aim of a seasonally-balanced heat charge and discharge of the geothermal storage is essential. Therefore, air heat pumps are included in the scenarios if the other heat sources taken into account would not be sufficient to reach the balance. These considerations lead to the scenario selection described in the results section. (4) In order to compare the environmental and economic performance of a heating and cooling system based on renewables and waste heat, a standard supply scenario based on gas boilers was introduced. A minimum solar heat contribution (1 m<sup>2</sup> collector per 100 m<sup>2</sup> useful floor area) was included.

The scenarios were defined upon the availability of local energy sources and stakeholder preferences as explained before. The relevant parameter for the formation of the scenarios was the seasonal heat energy balance. The calculations for the demand side as well as for the supply side (generation) were performed on an hourly basis as also typical daily fluctuations are of importance. These profiles were needed to calculate the necessary storage volume and associated losses. Hourly consumption profiles for domestic households throughout a whole year were provided by Vienna energy supply from measured profiles of a 90-apartment building in Vienna with similar energy demands. To estimate the future energy consumption of the planned buildings, the following assumptions were made: The annual energy consumption for heating in dwellings was set to 35 kWh/m<sup>2</sup>a which is a mean value for newly-built domestic buildings in Vienna according to Vienna energy supply, for non-residential, 45 kWh/m<sup>2</sup>a was assumed. The warm water energy consumption amounts to

12.8 kWh/m<sup>2</sup>a according to the national regulation [42], however, the experience of Vienna energy supply from residential multi-family houses showed that in reality, also because of circulation losses, 28 kWh/m<sup>2</sup>a are more appropriate, accordingly this value was taken. For non-residential buildings (predominantly offices), no warm water consumption was assumed as most of the (small) amount might be covered by local electric boilers and the consumption especially in offices is typically negligible.

The interaction of the different calculation methods and softwares leads to the determination of the energy balances. The hourly energy provision from the different sources was calculated separately: (1) The wastewater heat calculation was based on the hourly flow rates and temperature differences (between the actual temperature and 6 °C); (2) solar heat was calculated by Polysun; (3) for cooling only a monthly analysis took place as result of lack of official data for cooling degree days (equal distribution of the cooling load per month); (4) for air heat, the mean temperatures for Vienna from the period 1971–2000 were taken as the basis; the amount of air heat pumps levels out the annual energy balance; (5) for the heat pump electricity amount, a feed-in temperature of 30 °C was considered; the performance factors were calculated by the participating heat pump company and verified in the project group as well as in the stakeholder group; (6) as a result, an hourly heat surplus or deficit was calculated in Excel; (7) finally, these values were fed into the EED calculation for the seasonal storage.

### 2.3. Environmental Analysis

A rough environmental impact appraisal was carried out by calculating greenhouse gas (GHG) emissions, total primary energy demand, as well as non-renewable primary energy demand. The calculation of the environmental impact includes the direct emissions from the electricity (Austrian consumption mix) respectively natural gas consumption. Gains from PV respectively PVT production are subtracted. Emissions from the production and installation of the components were not included as most components are equal in all scenarios, and a materials' analysis was not part of the research. Residential and non-residential electricity consumption were not included in the analysis as this research focuses on the heating and cooling supply; only the electricity necessary for heating and cooling supply was considered.

The environmental impact of the designated scenarios was quantified using the following three categories:

- greenhouse gas (CO<sub>2</sub> equivalent) emissions
- total primary energy consumption
- non-renewable primary energy consumption

The coefficients were taken from the national Directive OIB 6 [43] in the version of 2019. The values are given in Table 4.

**Table 4.** CO<sub>2</sub> emissions and primary energy factors for electricity and natural gas according to Ref. [43].

Category	Electricity	Natural Gas
CO <sub>2</sub> equivalents (g/kWh)	227	247
PE total (kWh/kWh)	1.63	1.10
PE non-renewable (kWh/kWh)	1.02	1.10

### 2.4. Economic Analysis

The economic feasibility was calculated based on a full cost analysis. It includes capital, energy and maintenance costs. Costs which are present in all designated scenarios were not considered, i.e. costs for the distribution of heating and cooling energy after the planned heating/cooling stations, distribution pipes and floor heating panels in the buildings, etc.

The economic analysis was performed according to the standard EN 15459 [44] which is similar to the German standard VDI 2067 [45] and the Austrian standard ÖNORM M 7140 [46] and is based

on the calculation of annuities. The investment costs, lifetimes and maintenance costs (based on a percentage of investment costs) of the components, which were found to be distinctive between the defined scenarios, were analyzed.

The energy prices used are the average Austrian industrial prices for 2013–2015: 49 €/MWh for gas and 121 €/MWh for electricity. The annual real interest rate (difference between annual nominal interest rate and annual inflation) was set to 3% p. a. and the base period was set to 25 years. All prices are without VAT.

### 2.5. Presentation of Results to Decision Makers and Stakeholders

In the course of this project, decision makers were involved periodically. In order to increase the likelihood of the practical implementation of project results and their consideration by decision makers, stakeholder discussions identified the following aspects to be important: Providing examples of the successful implementation/realization of similar concepts; explaining the benefits of the involved energy provision and storage technologies; proving the technical feasibility of the concept in the dedicated area (e.g., sufficient energy potential available); showing environmental benefits compared to conventional approaches; and calculating the economic feasibility. These aspects were core issues in the project and were thus also addressed in detail during the final presentation. Decision makers had the opportunity to share knowledge and experience on the proposed approach. The consequent and permanent involvement is seen as a core success factor towards the realization of innovative heating and cooling concepts.

## 3. Results

In this chapter, the case study results are presented according to the project report [47]. In the following section, the investigated scenarios are described, followed by a presentation of the related energy balances for heating/cooling and electricity, showing the possible contribution of on-site renewables to the energy supply. This is followed by an analysis of the environmental impact, consisting of a CO<sub>2</sub> emission and a primary energy comparison. Finally, the economic feasibility is evaluated by comparing the full costs with the reference scenario over a 30-year period.

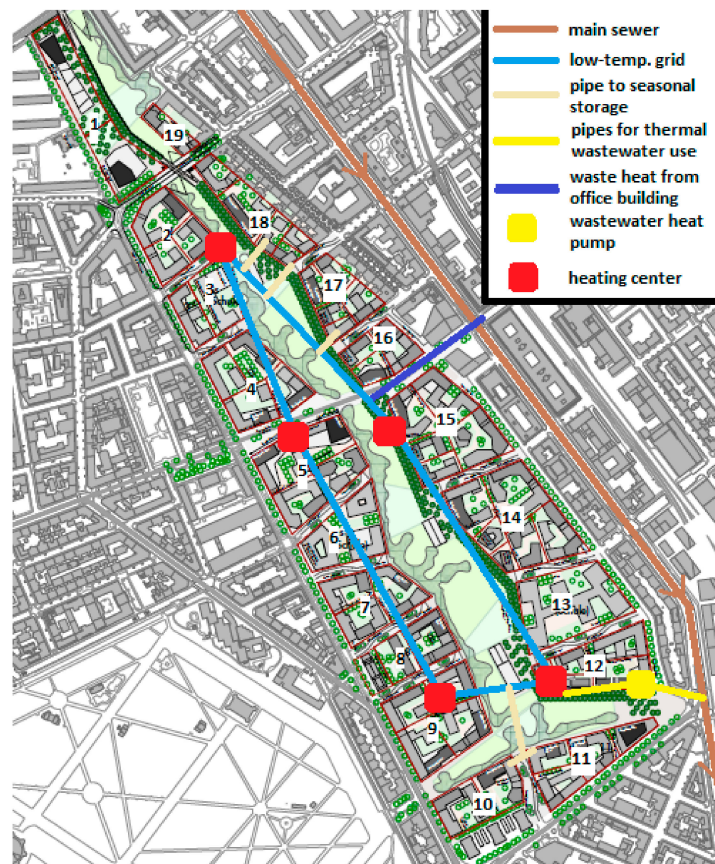
### 3.1. System Design—Scenario Development

In the following Figure 3, the case study site is again displayed including the intended positioning of the heating centers and the energy grid (both light blue), the pipe from the adjacent cooled office building (dark blue), the wastewater heat exchanger in the southeast (red), and the pipes from/to the geothermal boreholes (brown). Colours of buildings indicate their planned height (the darker the higher).

Taking into account the variety of available heat sources discussed before, different combinations can be considered. Furthermore, the evaluation of the contribution of fossil fuels was explicitly asked for by the City of Vienna for environmental and economic comparison. Four different combinations of the usage of the available renewable sources were compiled to form four scenarios plus a fossil, natural gas-based reference scenario.

All of the four scenarios include (1) solar energy in the form of PVT collectors respectively PV collectors, (2) wastewater heat, (2) ambient air heat in a quantity that balances the annual heat consumption together with the fixed amounts from the other sources as well, (4) waste heat from surrounding offices, and (5) geothermal boreholes for storing thermal energy. The scenarios differ concerning the dimensioning of heat pumps in the five heating stations between the low-temperature grid and the five local heat grids. Either they were dimensioned to the lowest expectable temperature in Vienna which is defined to be minus 12 °C expressed in a 2-day mean value, or the threshold was 0 °C (below this, gas heating boilers would cover a part of the heat load). As reference scenario, in order to compare the environmental and economic effects, a standard gas-condensing boiler with minimum solar thermal collector contribution according to the Viennese building law (1 m<sup>2</sup> collector per 100 m<sup>2</sup>

gross floor area) was considered. The main assumptions of the five scenarios are summarized in Table 5.



**Figure 3.** Overview on the intended energy supply system, adapted with permission from [31] OEGB (internal document): Vienna, Austria, 2019.

**Table 5.** Overview of the investigated scenarios.

		Scenario 1 (PVT)	Scenario 2 (PV)	Scenario 3 (PVT + Gas)	Scenario 4 (PV + Gas)	Reference Scenario (Gas)
Energy source	Solar energy	PVT	PV	PVT	PV	solar thermal
	Wastewater heat			yes		no
	Ambient air heat			yes		no
	Waste heat (from offices)	from one office building close to “Nordwestbahnhof” area				no
Storage	Geothermal			yes		no
	Area used for solar energy (m <sup>2</sup> )			30,000		0
Boundary conditions	Local electricity generation	PVT	PV	PVT	PV	no
	Design temp. of heat pumps in heating stations		−12 °C		0 °C	-

The heating and cooling energy is distributed via a two-pipe circular low-temperature (“anergy”) grid consisting of plastic material transporting water (without glycol). For heating purposes, pipe 1 serves as inlet and pipe 2 as return flow, whereas for cooling purposes, pipe 2 serves as inlet flow and



pipe 1 as return flow. As the temperature difference between grid and soil is approximately only 10 °C, no extra pipe insulation was considered. As the temperature levels of heating and warm water are different, extra pipes have to be foreseen. The advantage of multiple heating centers is that the length of warm pipes can be reduced remarkably and that more extraction points of heat from the grid lead to a more stable grid. If extra pipes between the heating centers are foreseen, the resilience of the grid is increased as a breakdown of one heating center can then be (at least partly) compensated; however, in each heating center, a cascade of heat pumps has to be installed, therefore, the resilience of one single heating center is already relatively high. The estimated power and energy consumption per heating center is shown in Table 6.

**Table 6.** Heating centers and attached blocks as well as energy and power consumption per heating center.

No. of Heating Center	Related Blocks (Figure 3)	Annual Energy Consumption (GWh/a)			Max. Power Consumption (MW)		
		Heating	Warm Water	Total	Heating	Warm Water	Total
1	1, 2, 3, 18, 19, 20	6.8	3.3	10.0	4.5	1.3	5.3
2	4, 5, 6	4.9	2.5	7.4	3.3	1.0	3.9
3	7, 8, 9, 10	5.7	3.6	9.3	3.8	1.4	4.7
4	11, 12, 13	5.9	2.2	8.1	4.0	0.9	4.4
5	14, 15, 16, 17	7.5	3.3	10.8	5.0	1.3	5.7
Total		30.7	14.9	45.6	20.6	5.9	23.9

The area used for solar collectors is equal in all four renewable scenarios (30,000 m<sup>2</sup>, about 7% of the total surface area); the difference is the technology used on this area (PV vs. PVT). The resulting annual energy output per m<sup>2</sup> is 152.8 kWh/m<sup>2</sup>a for electricity for PVT respectively 146.5 for PV and 450 kWh/m<sup>2</sup>a for heat for PVT. From the master plan of the development area, a total gross area of 93,000 m<sup>2</sup> was calculated. According to IEA [48], the usable roof area is 1/3, i.e., 31,000 m<sup>2</sup>. To be on the safe side, a value of 30,000 m<sup>2</sup> was agreed (also considering area for heat pumps). A horizontal assembly of the collectors was chosen as lower wind force would occur, assembly is easier, and self-clouding would be minimized. For instance, the example of Suurstoffi (CH) shows that this design is feasible and favourable [20].

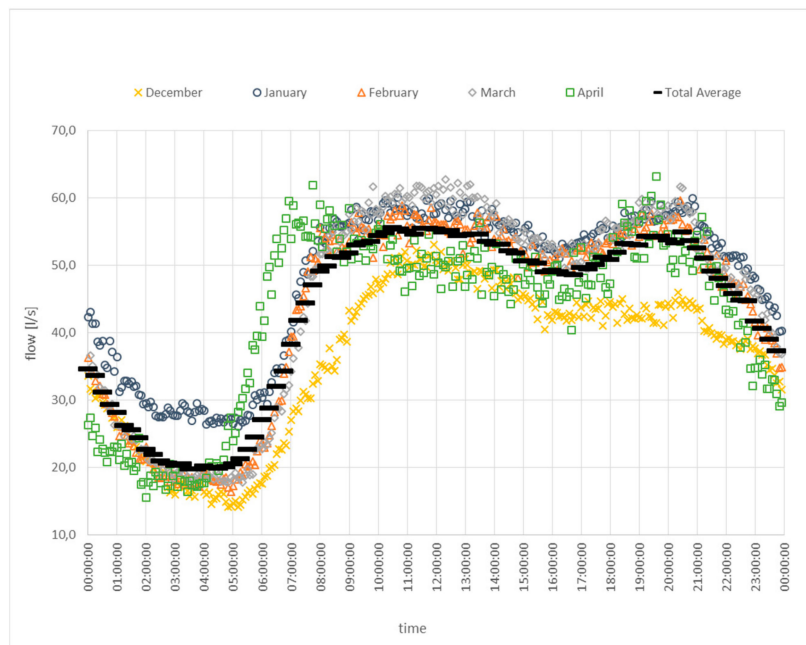
For a first (rough) assessment of the wastewater heat potential, an analysis of the catchment area was carried out. Statistical data [49] delivered an estimation of 23,900 inhabitants in the catchment area of the main sewer passing the investigated area. Moreover, a number of additional 4400 inhabitants of future “Nordwestbahnhof” residents were considered while offices, schools, etc. were excluded from the calculation. Applying a per-capita daily water consumption of 130 L resulted in an average dry weather wastewater flow of 42.6 L/s. For the first assessment, the local wastewater temperature was set equal to the one measured at the central WWTP (Table 7). For estimating the heat extraction (energy) potential, a remaining minimum wastewater temperature of 6.0 °C was defined among the project and stakeholder group.

**Table 7.** Monthly mean temperature of the wastewater inflow of the Vienna wastewater treatment plant [50].

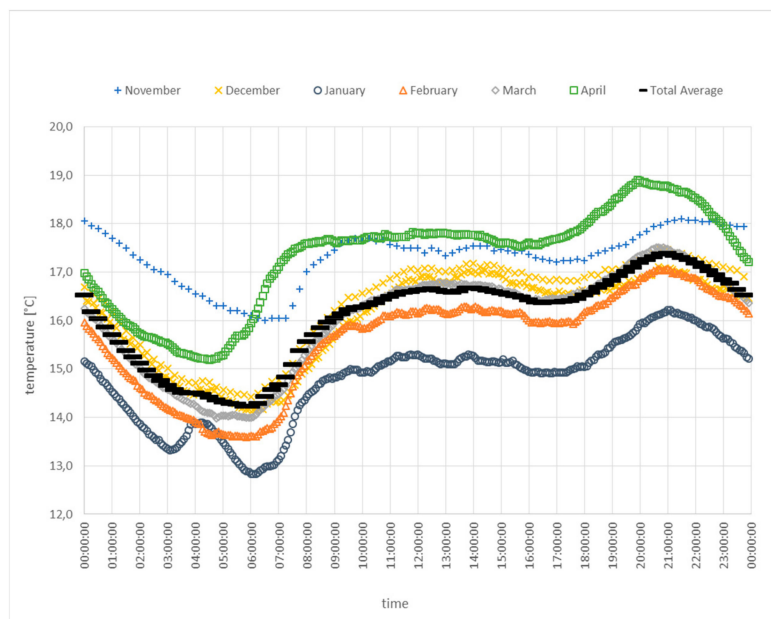
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
°C	13.0	13.0	13.0	16.0	17.0	18.0	20.0	20.0	19.0	17.0	16.0	14.0

In addition to the rough estimation, to gain a better insight on and understanding of the available wastewater heat potential, wastewater flow and temperature were measured during a 5-month

measurement campaign from 23 November 2015 to 28 April 2016. Figures 4 and 5 display the monthly and total average dry weather wastewater flow and temperature from this measurement period.



**Figure 4.** Monthly and total average dry weather wastewater flow from December 2015 to April 2016.



**Figure 5.** Monthly and total average dry weather wastewater temperature from November 2015 to April 2016.

Due to measurement problems, which could only be solved during December, Figure 4 does not contain the month of November.

The average diurnal flow patterns show a minimum discharge of about 20 L/s, a maximum of about 55 L/s and an average of around 43 L/s. This value matches quite well with the 42.6 L/s from the rough estimation (which was calculated with additional inhabitants on the Nordwestbahnhof quarter).

The average diurnal temperature patterns show a minimum slightly above 14 °C, a maximum of slightly above 17 °C, and an average temperature of around 16 °C. This value is even higher than

the one measured at the WWTP and used for the rough analysis and thus highlights the importance of on-site measurements for more appropriate estimations of the available heat recovery potential. Anyway, for detailed planning purposes, these data are being considered a basic prerequisite.

The air heat pumps show a large potential which is hard to quantify in total, however, they were foreseen in an amount that secures a heat balance over the year (extraction from the storage equals feed-in over the year) and, therefore, their number depends on the specific scenario. If air heat pumps with 94 kW power are considered (large standard product), the number of necessary air heat pumps in the whole “Nordwestbahnhof” area is according to Table 8.

**Table 8.** Number of air heat pumps depending on the scenario.

Scenario	1 (PVT)	2 (PV)	3 (PVT + Gas)	4 (PV + Gas)
Number of air heat pumps	14	36	11	34

The amount of waste heat from the office building was estimated to be 1.1 GWh/a based on data received from building users; for buildings to be erected in the development area within the Advisory Board, a consumption of 2 GWh/a was estimated. For the existing building, an extra pipe with a length of 130–150 m was necessary.

#### Geothermal storage

In total, 5439 boreholes with a depth of 100 m were necessary to close the time gap between production and consumption profiles. Forced cooling was applied with a temperature range between 6 and 22 °C.

#### Total energy consumption and generation for the different scenarios

As already expected, at the beginning of the research, the heating demand was much larger than the cooling demand. Therefore, additional heat sources were needed.

The potentials of the considered energy sources and the energy balances for the investigated scenarios are shown in Table 9 on an annual basis. The main result is that all heating and cooling demands can be covered by on-site renewable energy sources, even with skipping several sources as ground water and rivers.

To visualize the results, a graphical representation of energy fluxes for the example of Scenario 1, which is the preferred scenario according to the stakeholder discussions, is displayed in Figure 6. This graph shows the low energy losses of the overall system that can be explained by the low temperature of the storage and amounts to only 6.3% of the energy supply.

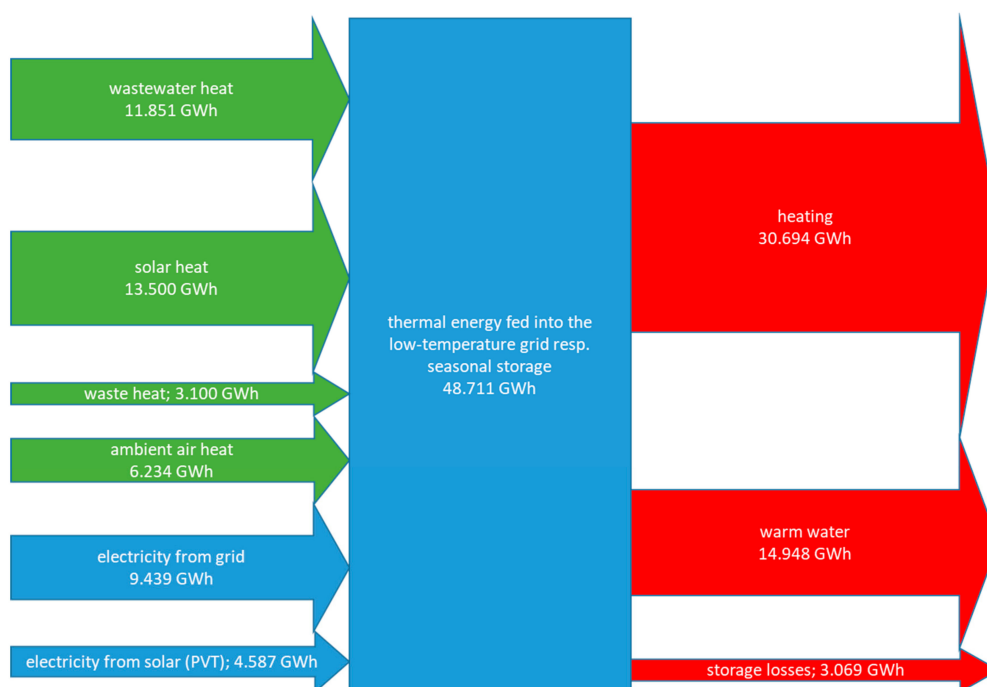
It might surprise the reader that in all scenarios there is a “perfect” heat balance (demand and supply exactly the same). This is due to the dimensioning/number of the air heat pumps and the gas boilers, respectively. The potential would be higher but was cut at the point where it equals the demand.

Although warm water contributes to the energy consumption to a large extent, and seasonal performance factors of the heat pumps were set to be rather conservative, a total seasonal performance of almost 3.5 could be reached for Scenario 1.

While the thermal energy can be produced on-site to 100% (when considering the electricity share used for the heat pumps), electric energy can only be covered partially on-site. Only about one third of the electricity needed for the heat pump operation can be generated on-site.

**Table 9.** Energy balance for the investigated scenarios: Red: Energy consumption; green: Energy provision by source; blue: Cooling demand; orange: Needed electricity for heat pumps; yellow: Natural gas consumption.

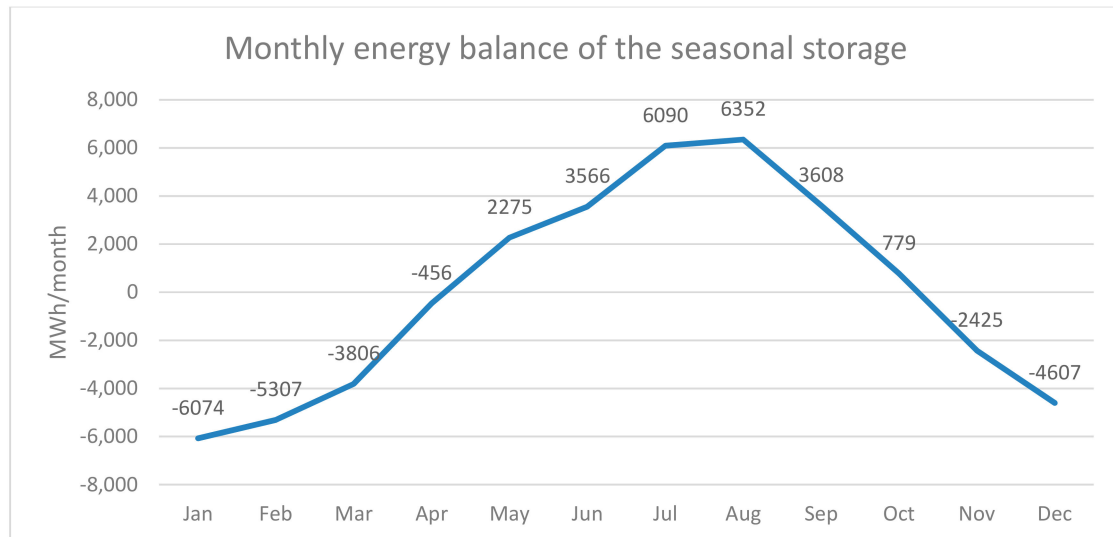
Energy Balance (Calculated from the Five Heating Centers) in GWh/a	Scenario 1 (PVT)	Scenario 2 (PV)	Scenario 3 (PVT + Gas)	Scenario 4 (PV + Gas)	Reference (Gas)
<b>Heating/Cooling Balance</b>					
room heating	30.694	30.694	30.694	30.694	30.694
warm water	14.948	14.948	14.948	14.948	14.948
storage losses	3.069	3.069	3.069	3.069	3.069
<b>total heat demand</b>	<b>48.711</b>	<b>48.711</b>	<b>48.711</b>	<b>48.711</b>	<b>48.711</b>
waste heat from cooling	3.100	3.100	3.100	3.100	-
solar heat (PVT, solar thermal)	13.500	-	13.500	-	2.250
wastewater heat	11.851	11.851	11.851	11.851	-
ambient air heat	6.234	16.862	5.009	15.637	-
<b>heat from local sources</b>	<b>34.685</b>	<b>31.813</b>	<b>33.460</b>	<b>30.588</b>	<b>2.250</b>
<b>heat demand coverage by local sources</b>	<b>71%</b>	<b>65%</b>	<b>69%</b>	<b>63%</b>	<b>5%</b>
waste heat pumps (offices)	1.550	1.550	1.550	1.550	-
wastewater heat pumps	2.047	2.047	2.047	2.047	-
air heat pumps	1.685	4.557	1.354	4.226	-
heat pumps in heating stations	8.744	8.744	7.900	7.900	-
<b>electricity for heat pumps (contribution to heat generation in the grid)</b>	<b>14.026</b>	<b>16.898</b>	<b>12.851</b>	<b>15.723</b>	<b>-</b>
<b>heat generation</b>	<b>48.711</b>	<b>48.711</b>	<b>48.711</b>	<b>48.711</b>	<b>48.711</b>
<b>demand coverage by local sources including heat pumps</b>	<b>100%</b>	<b>100%</b>	<b>100%</b>	<b>100%</b>	<b>5%</b>
cooling demand on site	2.000	2.000	2.000	2.000	2.000
external cooling demand	1.100	1.100	1.100	1.100	-
<b>cooling demand coverage by central grid</b>	<b>100%</b>	<b>100%</b>	<b>100%</b>	<b>100%</b>	<b>0%</b>
<b>gas</b>	<b>-</b>	<b>-</b>	<b>2.400</b>	<b>2.400</b>	<b>46.461</b>
<b>Electricity Balance</b>					
electricity for heat pumps (from above)	14.026	16.898	12.851	15.723	-
residential electricity demand	17.031	17.031	17.031	17.031	17.031
non-residential electricity demand	21.676	21.676	21.676	21.676	21.676
<b>total electricity demand</b>	<b>52.733</b>	<b>55.605</b>	<b>51.558</b>	<b>54.430</b>	<b>38.707</b>
<b>electricity generation</b>	<b>4.587</b>	<b>4.405</b>	<b>4.587</b>	<b>4.405</b>	<b>-</b>
<b>demand coverage of electricity</b>	<b>9%</b>	<b>8%</b>	<b>9%</b>	<b>8%</b>	<b>0%</b>



**Figure 6.** Graphical illustration of the thermal energy flows of Scenario 1 during 1 year.



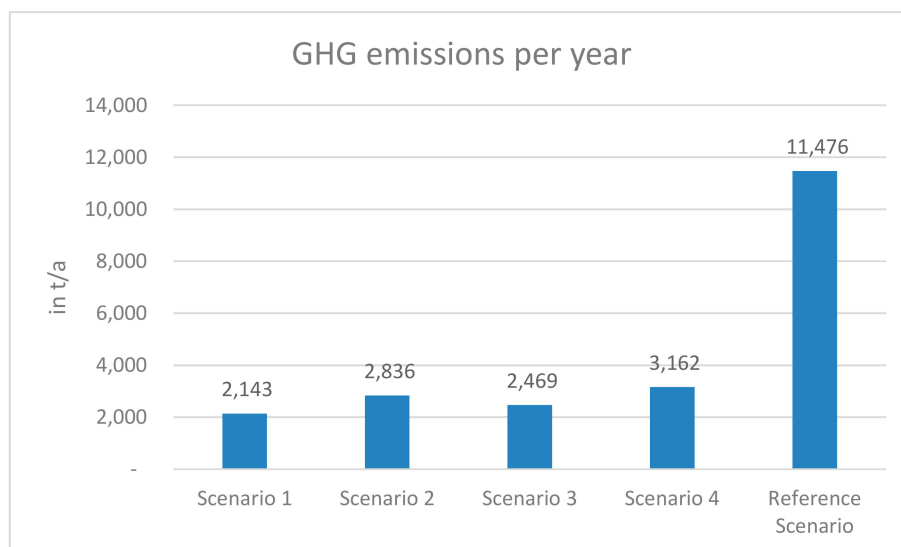
The monthly energy balance of the seasonal storage is shown in Figure 7. The overall annual balance is levelled out, i.e., the heat extraction equals the feed-in of thermal energy, securing a long-term stable ground temperature.



**Figure 7.** Monthly energy balance of the geothermal storage: negative values: energy extraction from the storage; positive values: feed-in to the storage.

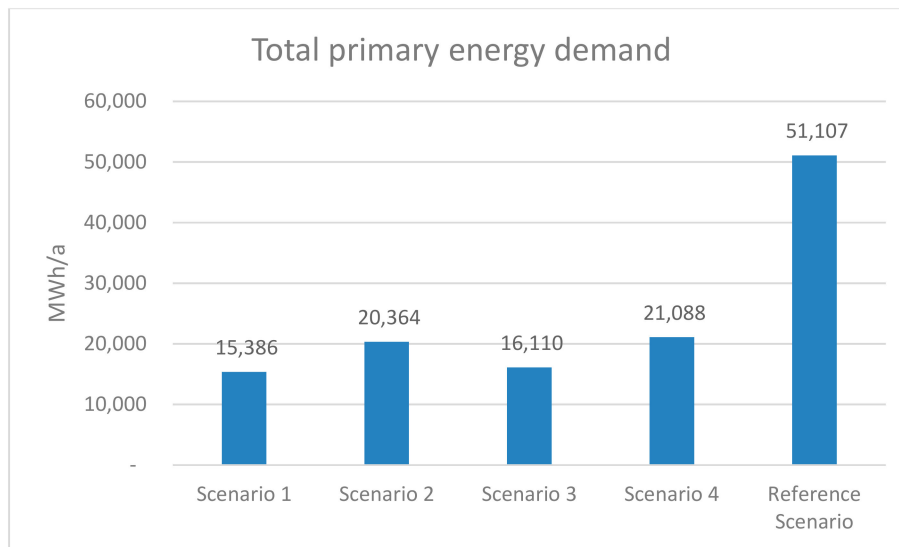
### 3.2. Environmental Impact

The following graphs show the annual CO<sub>2</sub> emissions and primary energy consumptions for the investigated scenarios resulting from heating and cooling energy generation. The GHG emissions (Figure 8) are lowest for the PVT option (scenario 1) and more than 80% lower than for the reference scenario.



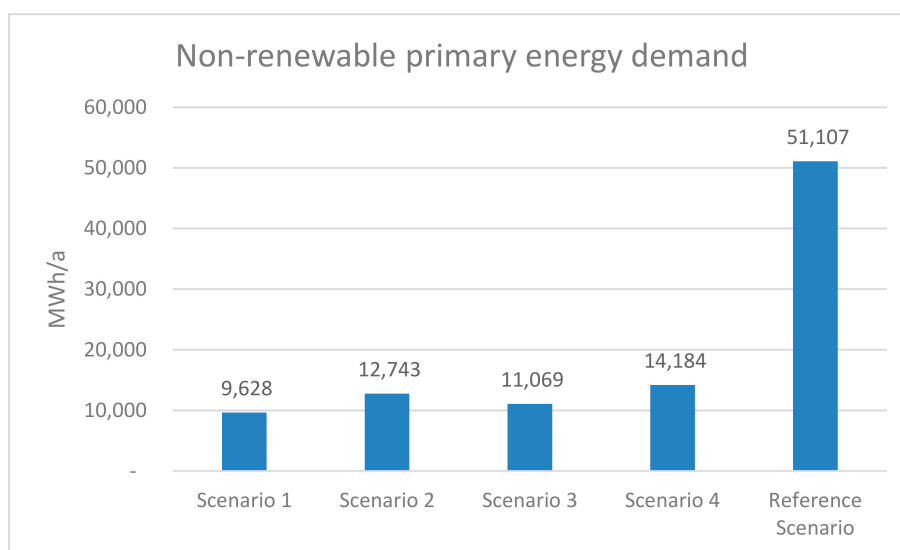
**Figure 8.** CO<sub>2</sub> emissions by scenario.

The total (renewable and non-renewable) primary energy consumption (Figure 9) shows approximately the same picture: The PVT option (scenario 1) has the lowest consumption and the value is 70% lower than for the reference scenario.



**Figure 9.** Total primary energy consumption by scenario.

For the non-renewable energy consumption (Figure 10), again the PVT option (scenario 1) shows the lowest value which undercuts the value of the reference scenario by more than 80%.



**Figure 10.** Non-renewable primary energy consumption by scenario.

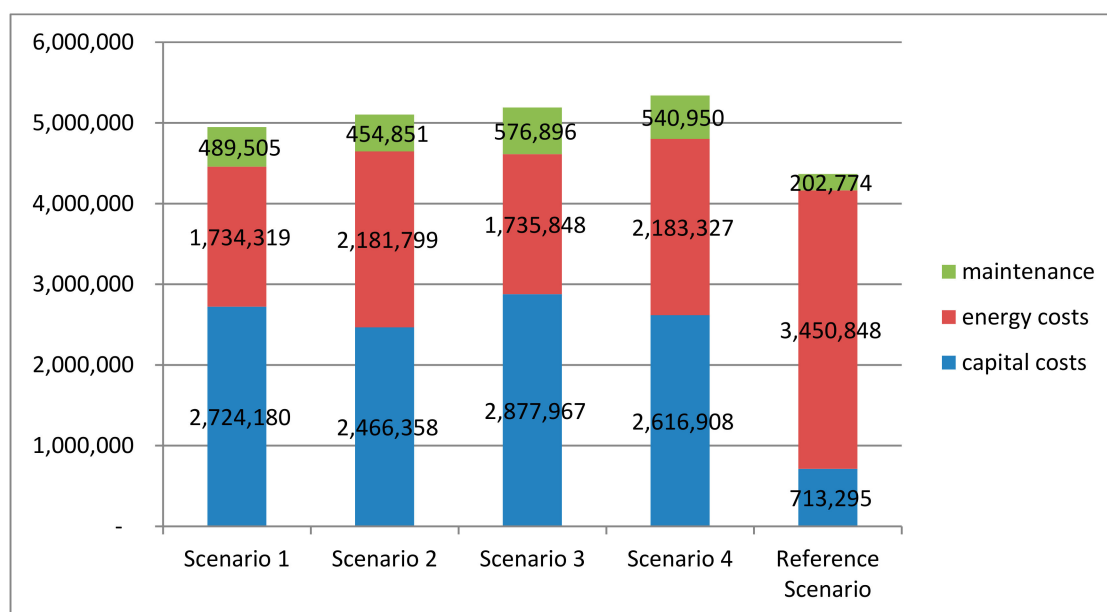
### 3.3. Economic Feasibility

Table 10 shows the investment costs for the components of the energy system which can differ between the scenarios. Components like heat dissipation systems, distribution pipes in the flats etc. which are equal to all 4 + 1 scenarios, were not considered, because they would occur in any heating supply system and would furthermore have required a detailed building modelling which was not possible at this stage of planning of the Nordwestbahnhof quarter.

**Table 10.** Investment cost groups for the five supply scenarios.

Cost Group	Scenario 1 (PVT)	Scenario 2 (PV)	Scenario 3 (PVT + Gas)	Scenario 4 (PV + Gas)	Reference Scenario
PV/PVT/solar thermal collectors	16,000,000	10,300,000	16,000,000	10,300,300	1,600,000
heat pumps	7,136,000	8,300,000	4,918,000	6,041,000	-
geothermal storage	14,350,000	14,350,000	14,350,000	14,350,000	-
small scale storages	500,000	500,000	500,000	500,000	300,000
pipes	3,800,000	3,800,000	3,800,000	3,800,000	1,200,000
gas infrastructure	-	-	5,241,000	5,241,000	6,778,000
space needed	4,650,000				
regulation	2,394,000	2,167,000	2,545,000	2,316,000	610,000
others	1,444,000	1,444,000	1,444,000	1,444,000	-
TOTAL	50,274,000	45,511,000	53,448,000	48,642,000	12,813,000

Figure 11 shows the resulting total annuity for the investigated scenarios. It is visible that the gas heating with minimum solar contribution (according to the legislation) is less costly. The difference comes from higher investment costs; i.e., the gap can be closed by investment funding. Costs during operation (energy and maintenance costs) are smaller for the four renewable scenarios.



**Figure 11.** Annuity costs in EUR/a per scenario, distinguishing between capital costs, energy and maintenance costs.

Normally, energy utilities like Vienna energy supply are calculated with lower base periods than 30 years. However, it was agreed to take longer timespans as such investments are long-term investments and public authorities can balance the difference by credits.

### 3.4. Presentation of Results to Decision Makers and Stakeholders

During the discussion after the final presentation of the results to the stakeholders, mainly the following topics respectively concerns were raised:

Reliability of the supply system: Some stakeholders had a bad experience e.g. from PVT collectors; additionally, the impact of the large number of geothermal boreholes on the geologic situation and the reparability were questioned. However, PVT collectors are the best way to make use of the limited area. The low number of PVT collectors compared to PV or solar thermal collectors might impair the

service quality and the ability to differentiate between high-quality suppliers and others. Still, there are a lot of suppliers on the market already and examples show that the systems work. The geologic situation in Vienna is well known and groundwater areas which might be a threat to the system only occur at a certain depth interval.

**Economic feasibility:** One of the biggest concerns regarded, apart from the fact that the full cost analysis showed that the proposed system was not fully competitive, was the high initial costs. The long-term benefits were acknowledged, but as low payback times are expected, initial costs play a more important role.

**Wastewater use:** Due to recent practical experience, the Vienna sewer operator only allows external heat exchangers today, i.e., the wastewater has to be extracted from the sewer, filtered and fed into a heat exchanger in a separate building (or in the basement of an adjacent house on the “Nordwestbahnhof” area). Because of the large size of the planned plant, external heat exchangers are the better option anyway, as a heat exchanger in the sewer would have to have a size of several hundred meters.

**Size of the project area:** Due to the novelty of the approach, stakeholders were reluctant to implement the system in an area of this size. It was discussed to test the options in a smaller development area first. However, after some months, Vienna energy supply started to investigate the opportunities of using wastewater heat in Vienna in more detail. This shows that even if the concept might not be realized 1:1, as suggested in this study, the results still influence decision makers and some new elements regarding heating and cooling energy supply systems will be adopted.

### 3.5. Summary of the Results

The principle idea of this research was to design a grid suitable for heating and cooling of an urban development area based on non-fossil fuels. By inclusion of a seasonal storage, the cooling demand (predominantly in summer) would serve as waste heat potential to cover heating demand (predominantly in winter) and heating demand would serve as “waste cool” potential to cover cooling demand. However, the results show that in a development area with mainly residential areas in central Europe, the heat demand exceeds the cooling demand by far, which makes it necessary to exploit locally-available renewables and waste heat sources from surrounding buildings to reach a balance. Reaching this balance is crucial, otherwise a long-term cooldown of the seasonal storage (consisting of geothermal sondes and the attached ground) would occur. Areas with a higher share of industrial or other non-residential areas may have a more equal heating and cooling demand, which would be favourable for such supply systems.

However, due to a variety of locally-available renewable and also waste heat sources from the surrounding areas, it is possible to balance the deficit and to secure that the heat storage, which is charged with heat by a necessary amount. Most of the heat sources are typically available in urban areas and allow the conclusion that low-temperature grid-bound energy systems are a feasible way to heat and cool most newly built urban quarters. Solar, wastewater and outside air are renewable sources with a high energy potential available in virtually all urban areas. As most are low-temperature sources, the use of heat pumps and low-temperature distribution and dissipation technologies is necessary.

As expected, the environmental impact measured in primary energy consumption and greenhouse gas emissions is a lot lower than using fossil fuels. Compared to heating with gas boilers, reductions of 70 to 80% are achievable. The results moreover show that at current market prices, economic feasibility can be reached, if subsidies or taxes in a reasonable amount are taken into account. It has to be mentioned that in quarters with higher cooling demand, the economic situation would be more favourable, so that areas with a high share of industry or offices implementing such systems already likely show economic feasibility without subsidies.



## 4. Discussion

The results from this research lead to the conclusion that considering a variety of locally-available renewable and waste heat sources allows covering the whole heating (and cooling) consumption of an urban area while electricity can only be covered partly. Low-temperature sources play an important role, and deviations between generation and demand profiles throughout the year necessitate the inclusion of seasonal thermal storages.

However, the crucial question is the generalizability of the results from this case study. Regarding the building structure and density, the investigated area can in many aspects be called typical for newly built urban quarters in large cities in Central Europe: There is a focus on buildings for domestic households; the energy standard according to the assumptions is average for new buildings, and the density is in a typical range for new quarters in large cities. It was considered within the project team and the advisory board that this development area, except for its size, is in many ways comparable to the other development areas in Vienna and in other larger European cities. Still, due to the specific framework conditions (mix of use, geometry, size, resources, etc.), it cannot, like any other specific area, be taken as a reference for the potential of renewables in other urban quarters. Therefore, the discussion covers two aspects: An interpretation of the case study results in forming a hypotheses for integrating energy demand and local renewable energy sources in smart urban development zones and a discussion on the strengths and weaknesses of the proposed planning approach.

### 4.1. Hypotheses for Designing Smart Urban Development Zones

#### 4.1.1. Heating and Cooling Energy (Apart from Electricity for Heat Pumps) Can Be Generated On-Site, While for Electricity There Is Typically Limited Potential

The results show that in this urban development area, the heating and cooling energy consumption can be covered by on-site renewables, whereas the electricity consumption can only be covered by 10%. As the cooling demand as well as the potential to use waste heat is very limited, which means they do not balance throughout the year, separate heat generation plants are necessary to reach a balance (like solar thermal plants, wastewater and air heat pumps). E.g., ETH Zurich [28] describes a comparable system with a lot of waste heat from laboratories where cooling and heating demand approximately balance throughout the year. Therefore, this case study can be seen as a worst case regarding the economic and environmental circumstances for a low-temperature heating and cooling grid. The fact that it is still (technically) feasible shows that this concept is appropriate for newly-built urban quarters.

#### 4.1.2. Main Heat Energy Sources are Solar Energy, Wastewater and Ambient Air

While solar energy and air are available in virtually all areas, wastewater, waste heat from cooling of surrounding buildings or on-site, ground water, and surface water from rivers/lakes etc. are very much dependent on the local case study situation. The investigated development area can profit from wastewater from outside the area itself, which is locally dependent, but still not an untypical factor (other areas have an even much larger wastewater related catchment area, especially if they are close to central WWTPs). Wastewater will always be available in urban areas. Consequently, solar heat, heat from outside air, and wastewater can be seen as standard heat sources in an urban development area.

Hybrid solar collectors (PVT) have the advantage of the highest area efficiency compared to solar thermal and PV collectors. This is why in quarters with limited areas for solar collectors, PVT is a way to maximize the output. The relatively low market share and subsequently lower competition and lower experience have to be considered.

The air heat pumps in this research were regulated following the outside air temperature. Another approach would be to turn on heat pumps when local electricity production is available. However, it was assumed that the low on-site production can mostly be used on-site and possible excess energy will rather occur when the outside temperature lies above 10 °C anyway. Therefore, maximizing the seasonal performance factor was the chosen option. If the 10 °C approach is appropriate in order to

secure the stability of the electricity grid also at a larger scale, it should be subject to further research. A different approach would be to design a system only containing air heat pumps and seasonal storages as the energy potential of outside air is high enough and the 10 °C approach secures high seasonal performance; however, optical and noise issues would have to be considered. Further research should be done on the limitations and advantages respectively disadvantages of this approach.

The high temperatures of wastewater even in wintertime indicates that wastewater is an energy source that should always be taken into account before other low-temperature sources like ground-soil, groundwater or outside air are considered. The seasonal performance of heat pumps using wastewater will be significantly higher as the temperature difference to the desired level is lower.

In densely-built areas with a mix of building functions it is quite probable that also waste heat from cooling or high-temperature industrial processes is available. The amount taken into account in this example is relatively low. Industry could not be found in the surroundings at all.

Groundwater and surface water from rivers or lakes would be theoretically available in the investigated area but were not taken into account as other more appropriate sources (by distance, complexity of energy system integration and temperature) were available. Small already-existing uses of ground water heat were identified as obstacles. It is recommended to the authorities not to apply the first come first serve principle because small plants block larger plants to an inappropriate extent.

#### 4.1.3. PV Is the Only Universally Accessible Electricity Generation Option in Urban Quarters

Regarding the electric energy consumption, the options are much more limited as low-temperature heat sources are not suitable for electricity generation. In this example, only PV respectively PVT contributes to the on-site electricity production. Other options would be geothermal energy (not promising in this area), water power (the Danube is already used energetically and not directly attached to the “Nordwestbahnhof” area) or wind (only small turbines could be feasible as for large turbines there are minimum distances from dwellings legally required). Therefore, it seems to be a difficult task to secure 100% on-site electricity production within a densely-built urban quarter, but this is not necessary if interactions of urban areas and their surroundings are taken into account. For instance, the Austrian renewable electricity generation amounts to 1881 kWh per inhabitant and year without large hydro-power plants and 5620 kWh including them [51–53], so that supplying the people of the new urban development area can at least be partly covered from a national perspective.

#### 4.1.4. The Importance of Low-Temperature Grids Will Increase, and They Are Necessary to Make Use of the Local Heat Sources

For many non-residential purposes, high temperature is needed. Still, for residential areas, the desired temperatures will decrease, especially in newly-built areas [54]. This gives the chance to use local low-temperature sources, distributed by fourth-generation district heating grids [21]. On the other hand, heat densities will decrease, unless building density is increased. Although the influencing factors are diverse and partially hardly to predict, an assessment of the future feasibility of district heating on a concrete area can be performed [55,56].

#### 4.1.5. Seasonal Storages Are Necessary to Balance Differences in the Annual Profiles of Demand and Supply. Sector Coupling Helps Balancing Profiles. Therefore, a Diverse Mix of Functions Is Favorable

The results show that the annual profiles of supply and demand, resulting from the use of locally-available renewable sources such as solar heat, wastewater heat, waste heat from offices or outside air, and considering a large share of domestic heating consumption, show large deviations from each other. Dimensioning the plants to the winter case would not be economically feasible, therefore, storages have to be implemented. As shown in this example, waste heat from offices can help balancing the energy system as well as industrial waste heat [17] or waste heat from data centers [18]. Sector coupling is therefore a key issue towards the realization of heating and cooling grids with renewable and waste heat sources.

The new EPBD directive [57] requires an assessment of the potential of load shift in buildings in order to assess the Smart Readiness Indicator (SRI) of buildings, which shows the high importance of load shifts and storage management with regards to buildings. The load shift potential can also be assessed quantitatively [58].

#### 4.1.6. Subsidies and a Change of Tax Systems Are Necessary to Promote Technologies Using Locally-Available Renewable or Waste Heat Sources

The example shows that renewable technologies tend to be more expensive at the beginning, but show economic advantages in the operation phase. Therefore, financing mechanisms have to take place in order to allow investors to cope with high initial costs. (Temporary) subsidies will in the long term lead to higher numbers of heat exchangers, heat pumps and heat storages, etc. which could lead to economic competitiveness against gas-heating systems even without subsidies.

#### 4.1.7. Stakeholders Have to Be Taken into Account Already at the Beginning

The final discussion of the project results revealed certain reservations and prejudices within the stakeholder group towards the realization of such innovative energy projects. The main reasons might be found in a lack of awareness. In this context, stakeholder discussions and information are of crucial importance [26]. However, also cost issues (economic feasibility) and concerns about reliability of the energy provision (customer satisfaction) are key concerns. The latter seems to be more critical as economic aspects can be covered by subsidies, guaranteed prices, etc., but risks during operation cannot be calculated. In principle, the approach of combining different sources and implementing large storages is highly diversified and therefore resilient. Also, the environmental benefits are obvious. These facts still have to be better communicated.

### 4.2. Strengths and Weaknesses of the Proposed Five-Step Approach

**System design—scenario development:** The proposed approach considers all locally-available renewable and waste heat sources (available energy potential), storage possibilities, as well as energy demands. It is therefore suitable to minimize fossil fuel usage in heating and cooling systems. The inclusion of a seasonal heat storage allows for the best possible use of the sources, and the detailed calculation based on hourly demand and supply data is a basis for the reliability of the results. The dimensioning of the system components was based on the maximum available amount of heat except for outside air. This was due to stakeholder discussions in which it was apparent that air heat pumps in large numbers are not a preferred option. However, different weightings (e.g. only using half of the wastewater potential, but installing more air heat pumps) could lead to more favorable economic circumstances.

**Energy balances:** For the investigated area, it was not possible to obtain more detailed data about the planned building uses, roof areas suitable for solar energy or air. If the plans change before realization, the results of this analysis cannot be used. This is also the reason why a detailed simulation of the grid and the consumers was not possible. Still, the general results which are of importance for urban development areas in general, are not affected by this.

**Environmental evaluation:** Regarding the environmental analysis, stakeholders and the project team agreed on a method focusing on direct emissions. Direct emissions contribute to the environmental balance to a large extent, especially in systems with fossil fuels. However, taking materials into account, a more refined analysis would have been possible. This was omitted as the relation between the four scenarios would have hardly been affected. Moreover, some components as PVT collectors would have been hard to assess and detailed pipe dimensioning was not part of this analysis either, making a wider environmental analysis questionable. Nevertheless, the achieved results show a clear enough picture and even the order of the four scenarios which are closely together would not be changed.

**Economic evaluation:** A full economic analysis would have included also heat distribution and dissipation systems in the buildings. As details about the buildings were not known, these components

were not included. However, they would be equal in all four scenarios. In the reference scenario, different components would be possible (higher possible inlet temperatures), but not necessary. Also, recooling components in the reference scenario were not taken into account.

Presentation of results to decision makers and stakeholders: The permanent involvement of stakeholders incorporates the views of experts in many different disciplines and is, therefore, besides the expertise of the project team itself, a further indicator of the high quality of the achieved results.

## 5. Conclusions

From this study, it can be concluded that it is technically possible to heat and cool with on-site renewable energy sources only (mainly heat from solar, wastewater and air), while the electricity consumption can only be covered by 10% as demonstrated on an urban development area in Vienna. However, a considerably high amount of electricity is also necessary for heat pumps to run the heating and cooling system. Rarely-used locally-available heat sources such as wastewater or waste heat from office cooling can play an important role in such systems. Especially favorable are quarters with approximately equally high heating and cooling demands during the year, as in this case, the need for separate heating generation sites is reduced. A low-temperature distribution grid for heating and cooling has been proven to be an appropriate and climate-friendly concept. Direct greenhouse gas emissions and primary energy consumption are remarkably lower than in a system with conventional gas boilers.

The energy supply of new urban settlement areas with on-site renewables will play a crucial role in the future in order to obtain resilience, independency of imports of energy carriers, and maximization of domestic value creation. Sector coupling of heat generation, housing, offices, and industry will facilitate the design and optimization of such energy supply systems.

One of the largest obstacles towards the realization of innovative energy concepts is the economic feasibility. Production sites relying on fossil energy sources are often less cost-intensive regarding the capital costs. However, during operation, renewable sources are beneficial as the “fuel” is often available for free (e.g., sun, air, wind, etc.). Therefore, the longer the base period taken into account, the easier the renewable solutions pay off. Lower interest rates are also beneficial as future surpluses then carry more weight. Subsidies should be technology-independent, just based on the environmental impact. In the “Nordwestbahnhof” case, economic feasibility without subsidies was not given, however, the cooling demand was very low which negatively affects the economic feasibility.

Still, economic questions are not the only obstacle towards the realization of renewable energy concepts. Applying new solutions to known situations can produce reservations because of a lack of knowledge regarding technical details, risk assessment, customer satisfaction, maintenance issues, etc. Therefore, the energy system design methods shall not only reveal optimal (technical) solutions but shall also allow stakeholders to learn about desirable futures and their role in realizing them. Therefore, stakeholders have to be included at the right point of time in an appropriate way in order to secure acceptance and a successful implementation (optimal social solution). Such concepts shall not be seen as competitive or even as a threat to established district heating systems or companies but rather as a chance for diversification and a route towards higher sustainability.

The results of the study clearly show that stakeholder management plays a crucial role in smart urban development. It includes the early selection of all relevant stakeholders, the continuous identification of knowledge gaps, and provision of information allowing for learning. Second, subsidies foster early stage consideration of novel supply concepts. Finally, policy makers should consider the adaption of legal boundary conditions like efficient energy use, compulsory use of local renewable energy, or the prohibition of new fossil energy installations as very powerful tools to accelerate smart solutions in urban development.

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evaluation of the wastewater measurement campaign. G.S. supported the conceptualization of this article and gave major input into the setup of the Discussion and the Conclusion.

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## References

1. Urban Europe—Statistics on Cities, Towns and Suburbs, 2016. Available online: [https://ec.europa.eu/eurostat/statistics-explained/index.php/Urban\\_Europe\\_-\\_statistics\\_on\\_cities,\\_towns\\_and\\_suburbs\\_-\\_executive\\_summary#City\\_and\\_urban\\_developments](https://ec.europa.eu/eurostat/statistics-explained/index.php/Urban_Europe_-_statistics_on_cities,_towns_and_suburbs_-_executive_summary#City_and_urban_developments) (accessed on 15 May 2019).
2. OECD. *Compact City Policies, A Comparative Assessment*; OECD Green Growth Studies; OECD: Paris, France, 2012. Available online: <https://www.oecd.org/greengrowth/compact-city-policies-9789264167865-en.htm> (accessed on 15 May 2019).
3. De Smet, I.; Laplume, D. Design of compact residential blocks for sustainable urban regeneration: Determination of consistent qualitative criteria. *J. Urban Regen. Renew.* **2019**, *12*, 248–257.
4. Samuelsson, K.; Colding, J.; Barthel, S. Urban resilience at eye level: Spatial analysis of empirically defined experiential landscapes. *Landsc. Urban Plan.* **2019**, *187*, 70–80. [CrossRef]
5. Stoeglehner, G.; Neugebauer, G.; Erker, S.; Narodoslowsky, M. *Integrated Spatial and Energy Planning Supporting Climate Protection and the Energy Turn with Means of Spatial Planning*; Springer Briefs in Applied Sciences and Technology; Springer: Berlin/Heidelberg, Germany, 2016. [CrossRef]
6. Statistik Austria. *Nutzenergieanalyse für Österreich 1993–2015*; English Translation: Analysis of Useful Energy for Austria; Statistik Austria: Vienna, Austria, 2016. Available online: [http://www.statistik.at/web\\_de/statistiken/energie\\_umwelt\\_innovation\\_mobilitaet/energie\\_und\\_umwelt/energie/nutzenergieanalyse/index.html](http://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/nutzenergieanalyse/index.html) (accessed on 8 July 2019).
7. Heat Roadmap Europe: Profile of Heating and Cooling Demand in 2015, Horizon 2020 Project. Available online: <https://heatroadmap.eu/> (accessed on 15 May 2019).
8. Center for Climate and Energy Solutions: Global Emissions. Available online: <https://www.c2es.org/content/international-emissions> (accessed on 29 July 2019).
9. Brown, T.; Schäfer, M.; Greiner, M. Sectoral interactions as carbon dioxide emissions approach zero in a highly-renewable European energy system. *Energies* **2019**, *12*, 1032. [CrossRef]
10. Gielen, D.; Boshell, F.; Saygin, D.; Bazilian, M.D.; Wagner, D.; Gorini, R. The role of renewable energy in the global energy transformation. *Energy Strategy Rev.* **2019**, *24*, 38–50. [CrossRef]
11. Erker, S.; Stangl, R.; Stoeglehner, G. Resilience in the Light of Energy Crises, Part I: A framework to conceptualise regional energy resilience. *J. Clean. Prod.* **2017**, *164*, 420–433. [CrossRef]
12. Erker, S.; Stangl, R.; Stoeglehner, G. Resilience in the Light of Energy Crises, Part II: Application of the regional energy resilience assessment. *J. Clean. Prod.* **2017**, *164*, 495–507. [CrossRef]
13. Guelpa, E.; Verda, V. Thermal energy storage in district heating and cooling systems: A review. *Appl. Energy* **2019**, *252*, 113474. [CrossRef]
14. Kretschmer, F.; Neugebauer, G.; Kollmann, R.; Eder, M.; Zach, F.; Zottl, A.; Narodoslowsky, M.; Stoeglehner, G.; Ertl, T. Resource recovery from waste water in Austria: Wastewater treatment plants as regional energy cells. *J. Water Reuse Desalin.* **2016**, *6*, 421–429. [CrossRef]
15. Kretschmer, F.; Weissenbacher, N.; Ertl, T. Integration of Wastewater Treatment Plants into Regional Energy Supply Concepts. *Sustain. Sanit. Pract.* **2015**, *22*, 4–9.
16. Rejeb, O.; Gaillard, L.; Giroux-Julien, S.; Ghenai, C.; Jemni, A.; Bettayeb, M.; Menezo, C. Novel solar PV/Thermal collector design for the enhancement of thermal and electrical performances. *Renew. Energy* **2019**, *146*, 610–627. [CrossRef]
17. Simeoni, P.; Ciotti, G.; Cottes, M.; Meneghetti, A. Integrating industrial waste heat recovery into sustainable smart energy systems. *Energy* **2019**, *175*, 941–951. [CrossRef]



18. Luo, Y.; Andresen, J.; Clarke, H.; Rajendra, M.; Maroto-Valer, M. A decision support system for waste heat recovery and energy efficiency improvement in data centres. *Appl. Energy* **2019**, *250*, 1217–1224. [CrossRef]
19. Ryberg, D.S.; Tulemat, Z.; Stolten, D.; Robinius, M. Uniformly constrained land eligibility for onshore European wind power. *Renew. Energy* **2019**, *146*, 921–931. [CrossRef]
20. Vetterli, N.; Sulzer, M.; Menti, U.-P. Energy monitoring of a low temperature heating and cooling district network. *Energy Procedia* **2017**, *122*, 62–67. [CrossRef]
21. Lund, H.; Werner, S.; Wiltshire, R.; Svendsen, S.; Thorsen, J.-E.; Hvelplund, F.; Mathiesen, B.-V. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy* **2014**, *68*, 1–11. [CrossRef]
22. Zambrano-Asanza, S.; Zalamea-León, E.F.; Barragán-Escandón, E.A.; Parra-González, A. Urban Photovoltaic Potential Estimation based on Architectural Conditions, Production-Demand Matching, Storage and the Incorporation of new Eco-efficient Loads. *Renew. Energy* **2019**, *142*, 224–238. [CrossRef]
23. International Energy Agency. *Heating—Tracking Clean Energy Progress*; International Energy Agency: Paris, France, 2019. Available online: <https://www.iea.org/tcep/buildings/heating/> (accessed on 31 July 2019).
24. Doubleday, K.; Hafiz, F.; Parker, A.; Elgindy, D.; Florita, A.; Henze, G.; Salvalai, G.; Pless, S.; Hodge, B.-M. Integrated distribution system and urban district planning with high renewable penetrations. *Wire's Energy Environ.* **2019**, *8*, e339. [CrossRef]
25. Cooper, L.T.; Rajkovich, N.B. An Evaluation of District Energy Systems in North America: Lessons Learned from Four Heating Dominated Cities in the US and Canada. Available online: <https://aceee.org/files/proceedings/2012/data/papers/0193-000354.pdf> (accessed on 16 September 2019).
26. Kretschmer, F.; Neugebauer, G.; Stoeglehner, G.; Ertl, T. Participation as a Key Aspect for Establishing Wastewater as a Source of Renewable Energy. *Energies* **2018**, *11*, 3232. [CrossRef]
27. Sameti, M.; Haghighat, F. Optimization of 4th generation distributed district heating system: Design and planning of combined heat and power. *Renew. Energy* **2019**, *130*, 371–387. [CrossRef]
28. ETH Zurich. *Anergy Grid*; ETH Zurich: Zürich, Switzerland, 2019. Available online: <https://ethz.ch/en/the-eth-zurich/sustainability/campus/environment/energy/anergy-grid.html> (accessed on 31 July 2019).
29. Amstein + Walthert. Richti Wallisellen. Available online: <http://www.richti.ch/downloads/Energiekonzept-Richti-Wallisellen.pdf> (accessed on 31 July 2019).
30. Stadt Wien (City of Vienna): Städtebauliches Leitbild Nordwestbahnhof [English translation: Urban Development Guideline Nordwestbahnhof]. 2008. Available online: <https://www.wien.gv.at/stadtentwicklung/studien/pdf/h000040c.pdf> (accessed on 24 July 2019).
31. OEBB (Oesterreichische Bundesbahnen—Federal Austrian Railways). *Written Communication from Mr. Andreas Dewath to the First Author of this Article on 09.09.2019*; OEBB: Vienna, Austria, 2019.
32. Neugebauer, G.; Kretschmer, F.; Kollmann, R.; Narodoslawsky, M.; Ertl, T.; Stoeglehner, G. Mapping Energy Resource Potentials from Wastewater Treatment Plants. *Sustainability* **2015**, *7*, 12988–13010. [CrossRef]
33. Ichinose, T.; Kawahara, H. Regional feasibility study on district sewage heat supply in Tokyo with geographic information system. *Sustain. Cities Soc.* **2017**, *32*, 235–246. [CrossRef]
34. eHYD: Hydrographie Österreichs [English translation: Hydrography of Austria]. Austrian Federal Ministry for Sustainability and Tourism. Available online: <https://ehyd.gv.at/> (accessed on 16 July 2019).
35. Available online: <https://www.velasolaris.com/?lang=en> (accessed on 15 July 2019).
36. Goetzl, G.; Fuchsluger, M. Existing Ground Water Usages around Nordwestbahnhof Limiting the Potential for a Large Ground Water Plant at Nordwestbahnhof. written communication to the project team in February, Geologische Bundesanstalt: Vienna, Austria, 2015.
37. Available online: [http://www.viadonau.org/fileadmin/content/viadonau/02Infrastruktur/Dokumente/2015/KWD\\_2010.pdf](http://www.viadonau.org/fileadmin/content/viadonau/02Infrastruktur/Dokumente/2015/KWD_2010.pdf) (accessed on 31 July 2019).
38. Pavlov, G.K.; Olesen, B.W. Seasonal Ground Solar Thermal Energy Storage—Review of Systems and Applications. In Proceedings of the 30th ISES Biennial Solar World Congress, Kassel, Germany, 28 August–2 September 2011; Volume 6, pp. 4864–4874, ISBN 978-161839364-7.
39. Oberle, A.; Krieg, S. Geothermal simulation of an energy pile system. *Geotechnik* **2015**, *38*, 152–159. [CrossRef]
40. Blázquez, C.S.; Martín, A.F.; Nieto, I.M.; González-Aguilera, D. Measuring of thermal conductivities of soils and rocks to be used in the calculation of a geothermal installation. *Energies* **2017**, *10*, 795. [CrossRef]

41. ÖNORM B 5019. *Hygienerelevante Planung, Ausführung, Betrieb, Überwachung und Sanierung von Zentralen Trinkwasser-Erwärmungsanlagen*; English translation: Hygienic planning, construction, operation, surveillance and maintenance of central drinking warm water supply systems; Austrian Standards: Vienna, Austria, 2017.
42. Austrian Standards. *ÖNORM B 8110-5: Wärmeschutz im Hochbau-Teil 5: Klimamodell und Nutzungsprofile*; English translation: Thermal insulation in building construction—Part 5: Climate model and user profiles; Austrian Standards: Vienna, Austria, 2018.
43. Österreichisches Institut für Bautechnik. *OIB 6 Richtlinie—Energieeinsparung und Wärmeschutz*; English translation: Energy saving and thermal insulation; Österreichisches Institut für Bautechnik: Vienna, Austria, 2019. Available online: [https://www.oib.or.at/sites/default/files/richtlinie\\_6\\_12.04.19\\_1.pdf](https://www.oib.or.at/sites/default/files/richtlinie_6_12.04.19_1.pdf) (accessed on 14 July 2019).
44. European Standard. *EN 15459: Energy Performance of Buildings—Economic Evaluation Procedure for Energy Systems in Buildings*; European Standard: Brussels, Belgium, 2008.
45. German Standard. *VDI 2067: Wirtschaftlichkeit Gebäudetechnischer Anlagen—Grundlagen und Kostenberechnung*; English translation: Economic efficiency of building installations—Fundamentals and economic calculation; German Standard, VDI: Duesseldorf, Germany, 2012.
46. Austrian standards. *ÖNORM M 7140: Betriebswirtschaftliche Vergleichsrechnung für Energiesysteme nach Dynamischen Rechenmethoden*; English translation: Economic comparison calculation für energy systems with dynamic calculation methods; Austrian standards: Vienna, Austria, 2013.
47. Urban pv+geotherm—Innovative Konzepte zur Versorgung großvolumiger städtischer Gebäude mit Photovoltaik und Geothermie [English Translation: Innovative Concepts for the Supply of Large Size Urban Buildings with PV and Geothermal Energy], Research Project. Available online: <https://www.energyagency.at/fileadmin/dam/pdf/projekte/gebaeude/Ergebnisbericht.pdf> (accessed on 17 September 2019).
48. IEA. *Potential for Building Integrated Photovoltaics*; IEA Photovoltaic Power Systems Programme; IEA: Paris, France, 2002.
49. Open Data Österreich: Katalog VIE-Bevölkerung nach Nationalität seit 2011 [English translation: Catalog population of Vienna according to nationality since 2011]. Available online: [https://www.data.gv.at/katalog/dataset/stadt-wien\\_viebevölkerungnachnationalittseit2011wienerzhlbezirke/resource/4f93cd16-972f-44b8-b987-b2d6b68fc4d6](https://www.data.gv.at/katalog/dataset/stadt-wien_viebevölkerungnachnationalittseit2011wienerzhlbezirke/resource/4f93cd16-972f-44b8-b987-b2d6b68fc4d6) (accessed on 2 August 2019).
50. EbS Wien. EbS Wien (2015): Monthly Mean Temperature of the Wastewater Inflow of the Vienna Wastewater Treatment Plant. written communication to the first author, EbS Wien: Vienna, Austria, 9 April 2015.
51. Bundesministerium für Nachhaltigkeit und Tourismus (BMNT). *Energie in Österreich 2018, Zahlen, Daten, Fakten*; English translation: Energy in Austria 2018, numbers, data, facts; Bundesministerium für Nachhaltigkeit und Tourismus (BMNT): Vienna, Austria, 2018; p. 18. Available online: [https://www.bmnt.gv.at/dam/jcr:3db9b813.../Energie\\_in\\_OE2018\\_Barrierefrei.pdf](https://www.bmnt.gv.at/dam/jcr:3db9b813.../Energie_in_OE2018_Barrierefrei.pdf), (accessed on 19 July 2019).
52. Statistik Austria. *Jahresdurchschnittsbevölkerung*; English translation: Average population per year; Statistik Austria: Vienna, Austria, 2019; pp. 1870–2018. Available online: [http://statistik.at/web\\_de/statistiken/menschen\\_und\\_gesellschaft/bevoelkerung/bevoelkerungsstand\\_und\\_veraenderung/bevoelkerung\\_im\\_jahresdurchschnitt/022311.html](http://statistik.at/web_de/statistiken/menschen_und_gesellschaft/bevoelkerung/bevoelkerungsstand_und_veraenderung/bevoelkerung_im_jahresdurchschnitt/022311.html) (accessed on 19 July 2019).
53. E-Control. *Statistikbroschüre*; English translation: Statistical brochure 2018; E-Control: Vienna, Austria, 2018. Available online: [https://www.e-control.at/documents/1785851/1811582/Statistikbroschuere\\_2018.pdf/7dee68bb-b2eb-16d5-9124-c5de5907a25d?t=1537774169540](https://www.e-control.at/documents/1785851/1811582/Statistikbroschuere_2018.pdf/7dee68bb-b2eb-16d5-9124-c5de5907a25d?t=1537774169540) (accessed on 16 August 2019).
54. Zach, F.; Erker, S.; Stoeglehner, G. Factors influencing the environmental and economic feasibility of district heating systems—A perspective from integrated spatial and energy planning. *Energy Sustain. Soc.* **2019**, *9*, 25. [CrossRef]
55. Lichtenwohrer, P.; Erker, S.; Zach, F.; Stoeglehner, G. Future compatibility of district heating in urban areas—A case study analysis in the context of integrated spatial and energy planning. *Energy Sustain. Soc.* **2019**, *9*, 12. [CrossRef]
56. Erker, S.; Lichtenwohrer, P.; Zach, F.; Stoeglehner, G. Interdisciplinary decision support model for grid-bound heat supply systems in urban areas. *Energy Sustain. Soc.* **2019**, *9*, 11. [CrossRef]

57. Official Journal of the European Union. *Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings Directive 2012/27/EU on Energy Efficiency; L156/75*; Official Journal of the European Union: Brussels, Belgium, 2018.
58. Maerzinger, T.; Oesterreicher, D. Supporting the smart readiness indicator—A methodology to integrate a quantitative assessment of the load shifting potential of smart buildings. *Energies* **2019**, *12*, 1955. [[CrossRef](#)]



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