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Smart energy systems for smart city districts: case study *Reininghaus District*

Stephan Maier

Abstract

Background: Dense settlement structures in cities have high demands of energy. Usually, these demands exceed the local resource availability. Individually developed supply options to cover these demands differ from place to place and can also vary within the boundaries of a city. In a common sense of European governance, cities are pushed to save energy, increase renewables and reduce import dependency on fossil fuels. There are many innovative concepts and technologies available to tackle these needs. The paper provides a comprehensive methodology for planning and assessing the development of 'smart' energy systems leading to complex energy provision technology networks using different on-site as well as off-site resources.

Methods: The use of the P-graph (process-graph) method allows the optimisation of energy systems by using different energy sources for heating, storing and cooling. This paper discusses this method in the development of an urban brown field, the premises of the *Reininghaus District*, a former brewery in the city of Graz in Austria. The case study is interesting as it combines on-site energy sources (e.g. solar heat and photovoltaic) with nearby industrial waste heat and cooling at different temperatures and grid-based resources such as existing district heating, natural gas, and electricity. The case study also includes the competition between centralised technologies (e.g. large scale combined heat and power and heat pumps with district heating grids) and decentralised technologies (e.g. small scale combined heat and power, single building gas boilers, solar collectors, etc. in buildings).
Ecological assessment with the Energetic Long-Term Analysis of Settlement Structures (ELAS) calculator provides an evaluation of the ecological impact of the developed energy systems.

Results: Different scenarios based on two building standards OIB (low energy house standard) and NZE (passive house standard) as well as different prices for key energy resources were developed for an urban development concept for the Reininghaus District. The results of these scenarios show a very wide spectrum of structures of the energy system with strong variations often caused by small changes in cost or prices. The optimisation shows that small changes in the setup of the price/cost structure can cause dramatic differences in the optimal energy system to supply a smart city district. However, decentralised systems with low-temperature waste heat and decentralised heat pumps in the building groups show the financially most feasible and, compared to alternatives, most ecological way to supply the new buildings.

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Correspondence: stephan.maier@tugraz.at
Institute of Process and Particle Engineering, Graz University of Technology, Inffeldgasse 13/3, 8010 Graz/Gradec, Austria

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Conclusions: The planning process for the development of the Reininghaus District is a complex and therefore lengthy process and shall be concretised over the next decades. Optimal energy technology networks and scenarios resulting from the application of the described methods support the framework energy plan. The accumulated knowledge can be used to form smart energy supply solutions as an integral part for the discussion of the stakeholders (investors, city department) to guide the forming of their action plan through the development of the city quarter.

Keywords: Smart energy systems, Urban energy systems, Process synthesis, Smart energy networks for urban areas, Use of waste heat and renewable energy, Sustainable Process Index

Background

Smart city approaches

Cities are the fastest growing form of settlement worldwide requiring sustainable energy systems to deal with their increasing density and size [1]. Although urban population growth in developed countries (0.5 %) is projected to be below population growth in less developed countries (2.3 %) from 2007 to 2025, there is a general shift from rural to urban areas; 60 % or 5 billion of the global population (8.4 billion people) will live in cities by 2030 [2]. This growth implicates a growing resource demand for buildings, infrastructure and energy supply in urban areas. City authorities are challenged worldwide because the demand for additional living and working space is rising.

The European Union provides different initiatives as well as funds and regulates by law how European cities should deal with these challenges in order to become smart cities [3]. The term ‘smart city’ was only developed quite recently. An exact approach to the definition of an optimal interpretation of ‘smart development’ and what ‘smart’ means for the city and its inhabitants is controversial. Every smart city design has a different focus on what ‘smart’ or ‘smarter city’ means and how to proceed with their specific development [4]. In this context, de Jong et al. gave a good overview about attributes which in the course of time have been attached to the word ‘city’ to name urban planning-related activities of researchers, decision makers and city planners, with definitions like *liveable*, *green*, *intelligent*, *low carbon*, *sustainable*, *digital*, *information*, *knowledge*, *resilient*, *eco* and *ubiquitous* [5]. They come to the conclusion that so far, most articles use the word *sustainable city* and since 2009, it seems to be replaced by the term *smart city*. From the organisational perspective, a differentiation of term *smart cities* was classified into the following two hierarchically counter-directed approaches [6]:

- *Top-down smart cities* are usually initiated by city institutions, information and communication technology (ICT) and/or research facilities, and it is a straight forward planning concept.
- *Bottom-up smart cities* are usually modelled by local inhabitants, and an innovative potential, societal knowledge and networks is used by the cities themselves to design the city.

A categorisation of a *smart city* so far is in many cases very technology-oriented putting expansion, improvement and integration of information and communication technologies in front of the attempt to *smarten* a city. However, with the difficulties that implementations of new technologies can pose also other aspects were added to the discussion. Some of the terms and ideas which are currently used in this relation are categorised [7]:

- General improvement of urban energy and planning concepts
- Environmental sustainability (sustainable resource use)
- Social sustainability (realising social inclusion of different kinds of urban residents in public services, citizen democratisation/cultural and societal empowerment)
- Higher quality of life through technical improvements in telecommunication infrastructure/administration/networks/living/mobility
- Economic development/efficiency
- Integrating private sector, business-oriented urban development
- High-tech/creative industries in long-term growth
- Social/relational capital in city development
- Adaptivity

Batty et al. classify the wide spectrum of terms and ideas which come up with the concept of ‘smart city’ and present and divide them into six functions [8]:

- Smart economy (competitiveness)
- Smart people (social and human capital)
- Smart governance (participation)
- Smart mobility (transport and ICT)
- Smart environment (natural resources)
- Smart living (quality of life)

Apart from the general observation of factual issues, it is the procedural setting which creates momentum in city development. Inside the functional framework, stakeholders can be identified as drivers in different institutions. Depending on their field of expertise, they have to deal with diverse contextual issues. In this relation, it is important to know which actor plays a role to which extent and how he or she is influencing the whole system of a city. In the Austrian research context, Saringer-Bory et al. categorise *Smart City Actors* in the *SmartCityAkteursmatrix (smart city actors matrix)* [9] as follows:

- Institutional category (public science, government, non-governmental organisation (NGO), private businesses, etc.)
- Field of expertise (spatial planning, architecture, urbanism, energy planning, mobility, climate research, social research, etc.)
- Keywords (energy standard, consumption, resources, renovation, insulation, networks, logistics, etc.)

In this respect, technological expansions of city infrastructure do not simultaneously imply improvements neither regarding sustainability issues nor the reduction of energy demand and increase in quality of life, wealth and benefit for the whole community [10]. There may be the risk that a smart city development is interpreted one-sidedly from a technical-business perspective only, and social and environmental requirements can be missed again. Smart city planners must not forget that just letting grow new businesses to produce *smart technologies* can have rebound effects so that social and environmental requirements of a sustainable urban development can be missed again. Environmental savings and social justice can be outweighed by an additional implementation of technologies whose main goal is to increase quality of life.

From an ecological perspective, the European regulatory states clear legal framework conditions for the communities of the European Union. One goal of the united European governmental efforts is to reduce greenhouse gas emissions by 20 % below the 1990 level by 2020 [11] and achieve a 40 % reduction by 2030 [12]. According to the European Parliament, buildings account for 40 % of the total energy consumption and 36 % of CO_2 emissions in the EU [13]. Low energy buildings and zero energy buildings could contribute to energy savings and emission reductions [14]. Hence, the EU passed the Energy Performance of Buildings Directive 2010 [15] and in the Energy Efficiency Directive 2012 stating that all public buildings by 2018 and all new buildings by 2020 must be nearly zero energy buildings. The laws clearly state that smart initiatives must include more than just adding smart grid technologies and technical process automation to the existing infrastructure. Holistic and sustainable system thinking needs to permeate widely through different levels of society. This requires a critical discussion on sustainable development and innovation itself and how theoretical sustainable concepts can be realised [16].

New approaches to build a framework to optimise new city quarters or rehabilitate existing urban quarters provide a holistic view to find smart, economically feasible energy systems with social and ecological benefits for the society. Different examples of attempts to build frameworks to push innovative planning concepts can be discovered in often closely related developments. These developments reveal a basic tendency of trying to push spatial planning closer together with energy planning. In Austria, the OEROK (*Oesterreichische Raumordnungskonferenz*/Austrian Conference on Spatial Planning) is an institution that was established by the federal government, the federal provinces and municipalities of Austria to coordinate spatial development on a national level. The OEROK started collecting and disseminating expert knowledge while raising awareness on the importance of *Energieraumplanung* (integrated spatial and energy planning) [17], as it is defined in the *Oesterreichisches Raumentwicklungskonzept*—OEREK [18]. The situation in Switzerland is similar to Austria: the programme EnergieSchweiz [19] provides a statement of requirements named *Energierichtplanung* (energy planning framework). In Germany, the term *Energienutzungsplanung* (energy utilisation planning), which is an energy usage plan to systematically develop future energy systems for municipalities according to specific local situations and renewable energy systems, first appeared in Bavaria in 2012 [20].

Across European approaches, an integration of energy and spatial planning is at different stages of development. Best practise examples and instruments for future-oriented and resource-efficient energy and spatial planning have already been defined and discussed by various authors [21]. An integrated spatial and energy planning process needs to integrate a reduction in the dependence on fossil fuels and an extended use of urban energy resources in comparison to the current state. Renewable energy technologies utilising industrial waste heat can be considered as they can provide positive impacts on local economy and reduce ecological burdens as well [22].

Planning and implementation of smart urban energy systems, however, involves a wide spectrum of stakeholders: from city administration to developers to energy providers to current as well as future inhabitants. The planning discourse between these stakeholders can be supported by reliable and comprehensive methods to design and evaluate complex energy systems. Such decision support methods

- Provide answers to the different perceptions of the economic framework for the development of smart energy systems brought to the table by various stakeholders by creating reliable scenarios
- Allow comparison of the scenarios by guaranteeing optimal energy systems generated by using different resource options and economic frameworks
- Provide comprehensive ecological evaluation of the scenarios along with thorough economic and technical specification to enable a holistic planning process

An approach to support stakeholders and policy makers with a selection and an application of different methods for an integrated spatial and energy planning is provided by Stoeglehner et al. in a study which gives an overview about tools which cover analysis of energy savings, energy efficiency, renewable energy, spatial planning, mobility and evaluation and optimisation of planning schemes [23].

Smart energy planning

Energy planning that leads to 'smart' urban solutions requires integration of energy design into spatial planning and urban planning. This means that the design of new settlements, as well as the refurbishment of existing city quarters, requires an interdisciplinary planning approach that takes spatial and mobility planning, energy systems design, building and infrastructure design and the evaluation of ecological impacts into account [24]. Innovative approaches must therefore be applied. Electricity supply in urban areas has moved to the centre of debate on how to supply urban areas with renewable energy [25]. Heat integration and heat storage, the integration of industrial waste heat and solar thermal energy in supply networks have also become major aspects of smart city development [26]. The case study region of *Reininghaus District* has already been in the focus of scientific endeavours to merge all these aspects [27]. The following tools and methods have been applied to the framework energy plan for the Reininghaus District allowing for systemic energy system design and holistic ecological evaluation.

For the investigated area, total energy demands are needed as important basic information to optimise the energy technology network. A further downscale to the building level is essential to focus on the level of a city quarter. In Austria, the OIB-standard, set by the Austrian Institute of Construction Engineering [28], is the minimum requirement regulated by Austrian law. The maximum energy consumption is continuously being lowered to reach EU regulation goals within the next few years. To constantly decrease energy consumption per building, energy demand levels permitted by the current Austrian Low Energy Building Standard (OIB-standard) and the Nearly Zero Emission Buildings Standard (nZEB or NZE-standard) are under ongoing discussion. In the interest to guarantee a better readability in this work, the phrases 'NZE-standard' and 'OIB-standard' will be consistently used. To avoid misunderstandings, each part of the phrases is connected by a hyphen. Improvements which can be applied to save energy in buildings can be reached, for instance with energy efficiency measurements such as optimised insulation building retrofit [29]. The focus of the optimisation of a whole city quarter's energy technology network needs to be extended from single house level to building groups. This is particularly important because small-scale modelling differs greatly from large-scale optimisation. Examples of how settlements could be designed and supplied with renewable energy often applied single technology approaches and partly hybrid renewable supply systems [30].

These approaches clearly highlight the importance and requirement for developing strategies and concepts to help city stakeholders with their burden of finding an optimal and secure future energy supply. Even though this paper is concerned with the challenges posed by these concepts, it also discusses an approach that is generally applicable to the selection of spatial planning processes. The paper considers the optimisation of renewable and fossil technologies along with specific conditions of the optimised city district, such as resource availability, competition and market prices.

Research problem

The research questions posed in this case study is the integration of available local energy sources into the energy system in order to meet future Reininghaus District demands. Three companies, which produce waste heat at different temperature levels, are located close to or even directly in the area: Steel plant *Marienhütte Stahlwerk*, which is already connected to the district heating grid of Graz, produces heat of approximately 80 °C, *Linde Gas* heat of around 20 °C and *STAMAG Malzfabrik* of around 20 °C. Additional waste heat in large amounts is available from the steel plant at a temperature of 30 °C. A cooling stream of 10 °C (which could also be used for upgrading in a heat pump) is available from groundwater wells left over from the former brewery within the district premises.

For a more precise approximation of different local differences, the Reininghaus District was split into 17 groups of buildings as they will be described in the case study description in chapter 3. After defining possible energy demands for the planned groups of buildings, the availability of local energy (e.g. waste heat, geothermal energy and rooftops for solar energy) and existing energy infrastructure to supply Reininghaus District was modelled. The district can easily be connected to the existing district heating grid of the city, currently supplied mainly by three large gas-, coal- and oil-fired combined heat and power (CHP) plants. The gas-fired plant (250 MW thermal power) is located within the city, and the coal (230 MW thermal power) and the oil-fired plant (230 MW thermal power) are located 20 km south of Graz [31]. Approximately 90 % of the district heat in Graz is generated from fossil fuels. Natural gas and electricity grid connection is also possible for the district. The model must provide consistent, economically optimal structures of the network between all possible sources, distribution within the quarters, conversion technologies and consumption. It takes seasonal variations into account. Subsequently, the optimal structures generated for different economical frameworks (scenarios) are ecologically evaluated.

Methods

Many approaches focus on smart energy system *design* and smart energy systems as a priori 100 % renewable systems (e.g. Lund et al. [32]). To keep the door open to compare existing energy regimes and infrastructure like fossil energy systems, the pre-definition of a specific target resource system was avoided in this work. The aim of this methodological framework is to provide information about optimal technology networks and the ecological and socio-economic evaluation of different options for future city developments. It consists of the Process Network Synthesis (PNS) and, inter alia, the tool Energetic Long-term Assessment of Settlement Structures (ELAS), the tool applying the Sustainable Process Index (SPI). In order to achieve the research goals raised in the framework plan to find smart and sustainable energy systems for cities, the PNS was chosen. With this method, it is possible to model complex systems and find *optimal energy systems* before studying the relevant matters in depth with the help of a modelling or design process. On the other hand, ELAS and SPI can deal with interdisciplinary issues of complex settlement structures and a comprehensive ecological evaluation. Process cycles of various energy systems can so be ecologically evaluated and provide usable information and a practical model for a stakeholder process.

Process Network Synthesis (PNS)

One method in particular that has proven its worth in planning tasks like integrated spatial and energy planning is PNS [33]. This method has been developed in the framework of process technology [34]. The mathematical structure behind has been discussed in several publications [35]. It uses a directed bipartite graph (p-graph or process-graph) method to describe process networks and employs combinatorial rules to find all feasible network solutions using all possible resources, intermediates and products as well as all relevant technologies processing these mass and energy flows (superstructure). Software employing this method (PNS Studio) is freely accessible from www.p-graph.com [36]. All data concerning flows and cost of technologies, pipes and transport can be provided in predefined material and operating units input tables of PNS Studio. Moreover, parameters like the required and maximum flows, lower bound and upper bound of capacity constraints for operating units can be set. Flows are split into resources, intermediates and products. Flows can then be set as input and output flows in the operating units to display conversion and production interdependencies between the technologies considered.

Figure 1 shows how the user-defined maximum technology structure is then the starting point for a rigorous

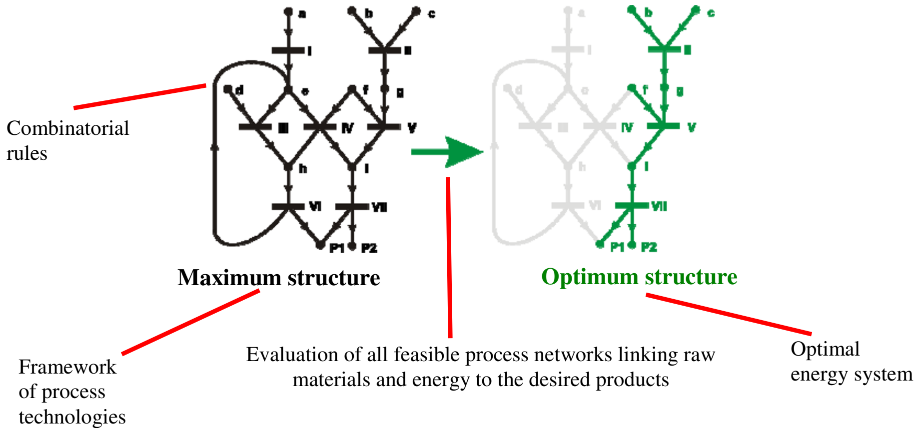

Fig. 1 Maximum structure and optimum structure of a technology network

evaluation of all feasible process networks linking resources to the desired products. The first step is the generation of a pre-optimisation of a feasible maximal process network (maximum structure) with the maximum structure generator (MSG), and in a second step, the optimal process network (optimum structure) is generated using a branch-and-bound optimisation included in the solver of PNS Studio.

In addition to its long tradition in process industry applications, PNS has also been successfully applied to regional resource utilisation problems [37]. A special software tool using the PNS method (RegiOpt) was recently developed [38] to provide a preliminary design for smart regional energy systems based on renewable resources and is freely available on the internet [39].

In this study, an in-depth modelling is carried out to generate scenarios for the optimal energy supply of the Reininghaus District using PNS. This method allows the optimisation of local energy and material demands and supplies situations represented in energy technology networks. Seasonal variations in resource provision and consumptions are treated by a multiperiodic option of the PNS [40].

ELAS calculator

ELAS was developed to analyse urban structures ranging from single houses to whole settlement structures regarding their energy situation and in particular their ecological performance. The calculator allows the evaluation of single buildings as well as whole settlements. It can be applied to existing structures as well as planning tasks and also allows the evaluation of refurbishing and extension plans to existing settlements [41].

The calculator takes site-specific data of residential settlements into account. This consists of energy consumption and supply, mobility induced by the location of the settlement as well as the distances to service provision. It uses a life cycle approach to the evaluation and accounts for the ecological impact of construction, use and disposal of all buildings and energy infrastructure in a settlement, such as roads, wastewater drains and lighting of public space.

Results of the ELAS calculator contain accumulated energy demand, ecological footprint (calculated with the SPI method) [42], CO_2 life cycle emissions and regional economic impact (turn over, value added, imports, jobs created or lost) of the settlements. The Sustainable Process Index is an ecological footprint method. It has recently been described and discussed in its international methodical context [43]. The SPI has been applied in several fields such as ecological evaluation of agricultural products [44] or collectively shown in the evaluation of energy technology systems based on renewable resources [45]. The ELAS calculator is an online tool that runs SPI evaluations in the background (along with other technical parameters and statistical variables) [46]. The ELAS calculator allows users to provide specific data via a GUI (graphical user interface).

ELAS provides municipalities a basis for sustainable energy supply and appropriate policy decisions or gives an overview of individual energy consumption and its economic and ecological effects. The tool is freely available online.

The result of the optimal structure of PNS obtained for a particular set of economic boundary conditions (a scenario) is used as input for ELAS evaluation. Amounts of resources (in this case, energy flows for the supply of the city quarter) resulting from PNS are one input for the assessment with ELAS calculator. In addition, the input parameters for ELAS are the site-specific data, building standards, infrastructure, induced mobility and energy, construction and mobility costs. Results are the ecological footprint (SPI), energy demand and CO_2. The total sequence proceeds as shown in Fig. 2.

Case study description

Graz, the capital of the Austrian Federal State of Styria is a middle-sized city (approximately 280,000 inhabitants by 2016 [47]) that is estimated to reach approximately 325,000 inhabitants by 2030, which would result in an increasing demand of living and working space [48]. In order to meet the growing population’s needs, the city planning department is required to densify the city preferably in a vertical manner. A horizontal extension should be excluded from spatial planning. According to the City Government, a horizontal densification is allowed for new buildings only. Following this urban areas already dedicated as building land are currently under heavy exploitation. Some of the existing building ensembles have been designated a UNESCO heritage site, whereby they are subordinated by law according to the *Dachlandschaftsverordnung* [49]. This law protects the urban roofscape, particularly in central parts of the city. These old buildings must be conserved, meaning an addition of storeys is not permitted there.

Most of the Reininghaus District is green- and brownfield, measuring an area of 110 ha. Reininghaus District is located 1.8 km west of the historical city centre, and approximately 12,000 inhabitants are predicted to live there after completion of all developments. The development of this new city quarter is carried out by an interdisciplinary team, consisting of scientists, architects, developers and experts from various stakeholders. For the part of the scientific support, a consortium of Graz University of Technology is integrated in the project Energy City Graz, which is a sub-project of the flagship project Energy City Graz (ECR). The Reininghaus project is funded by the Austrian state research and

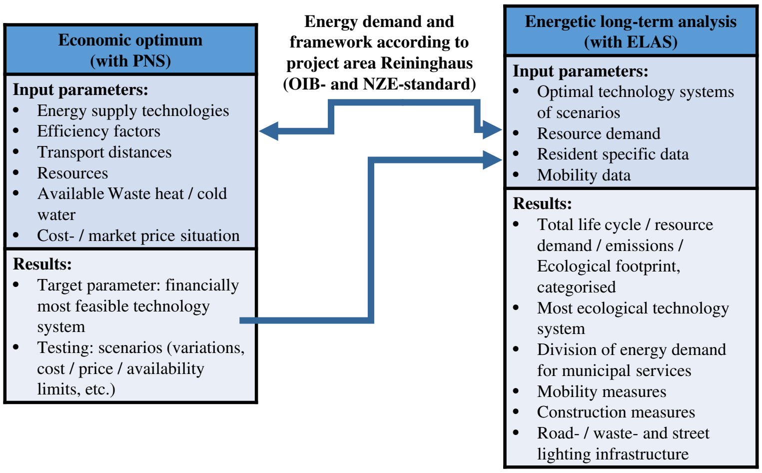

Fig. 2 Methodical framework

technology programmes Building of Tomorrow and City of Tomorrow [50].

The case study carried out in this project is an integral part of the framework energy plan City Graz Reininghaus [51]. This framework plan covers:

- The concept of a self-sufficient, in terms of energy, city district, the initiation and supervision of the development process for the energy-optimised and sustainable city district Graz-Reininghaus, the phrasing of guidelines, recommendations and a checklist for future energy optimised city developments in Graz and Styria
- The development of specific energy values in private legal contracts between the city of Graz and future investors, promoted by incentive systems like bonus cubage and higher housing density for buildings
- Concepts for the integration of the energy values in suitable manner in local plans and regulations (City Development Concept STEK Graz, City-District-Development-Concept Graz-Reininghaus and development plans for the city quarters on location)

Graz city officials have announced the intention of using the plan to define an innovative framework for the development of the Reininghaus District [52]. The outcome of the complete framework energy plan includes possible energy technology network solutions as well as architectural, mobility, environmental and infrastructural guidelines.

The forming of the optimal building characteristics by an interdisciplinary team played an important role to provide a basic model and let heat and electric experts calculate energy needs of the new quarter. Generally, a perimeter block development was chosen as a basic building concept for all groups of buildings. To guarantee individuality for the specification of the building characteristics for each group of buildings, an architectural competition was performed for the first groups and will be announced for the other groups of buildings over the next years or decades. Depending on side-related issues, the cubature and spatial planning aspects of each building and group of buildings were adapted related to the expected context (mixture of utilisation including open green areas, mobility, air quality issues, wind, shadowing effects, etc.). In coordination with the framework plan, superordinate goals such as for the whole district Reininghaus could so be followed. Apart from the energy technology network solutions, the other guidelines are not part of this work. Information directly important to form the context of this work is provided here. A detailed description of it can be found in the framework energy plan.

For the framework energy plan, the city district Reininghaus was divided into 17 groups of buildings consolidated in three geographical districts: North, East and South as shown in Fig. 3. The group of buildings feature homogenous parameters, like energy standards for buildings, functional mixes, load profiles for heat and cooling, defined in the university consortium, which serves as the guideline for development. They are individual components in the model described in this study. Within these groups of buildings, average distribution distances for linking buildings to energy grids are assumed. For the larger geographical districts, it is necessary to define the overall structure of distribution grids for natural gas, district heating, electricity and wastewater collection systems as well.

This paper presents a model that identifies the optimal technological network as well as locations for energy provision installations, which

- Provide all groups of buildings with heat and electricity

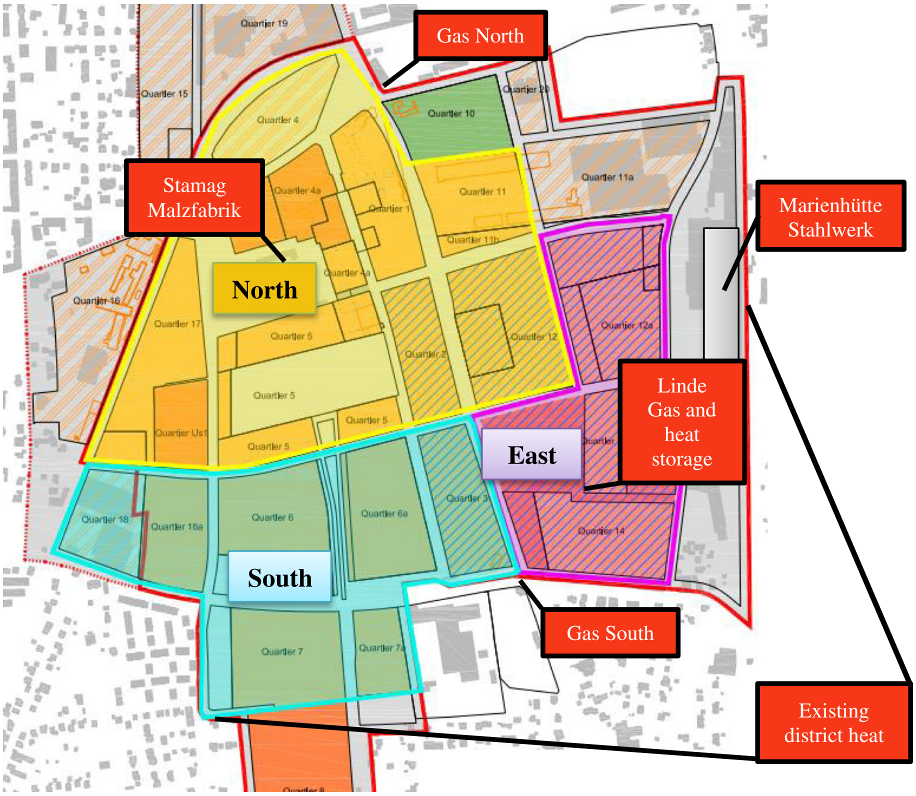

Fig. 3 Three geographical subareas N, E and S including 17 groups of city buildings

- Integrate locally available resources while generating the highest possible value added for the whole energy provision system of the total district Reininghaus
- Take resource, investment and infrastructure costs as well as limitations of (and possible competition for) resources into account

This model may be used to develop consistent optimised scenarios for different economic framework configurations and evaluates them economically and ecologically. The scenarios serve as a solid basis for negotiations between the various stakeholders, whose interactions will shape the district's future smart energy system. The goal of using this model is to provide stakeholders and decision makers with a factual basis for a discourse on the development and implementation of a smart energy system in this brownfield development project.

The energy aspects of the framework plan for the Reininghaus District brownfield development is based on the following premises:

- The framework plan includes options for OIB-standard buildings (52.6 kWh/y.m^2 heating and 4.6 kWh/y.m^2 cooling demand) and NZE-standard buildings (11.2 kWh/y·m^2 heating and 11.4 kWh/y·m^2 cooling demand) as a basis for the calculation of the energy demand of the group of buildings.
- Load profiles for heating and cooling are taken into account.
- Existing sources of industrial waste heat shall be taken into consideration for optimal energy systems.
- Additional infrastructure to utilise waste heat (e.g. distribution pipes) is accounted for.
- A scenario presuming autarky (at least for cooling and heating) has to be provided for reference.
- The model generating the scenarios forming the basis for the stakeholder discourse takes capacity limits and qualities of local energy sources into consideration.

The framework plan is the result of an intensive discourse between stakeholders in the Reininghaus District development, taking long-term trends in the economic and environmental framework for supplying and using energy in this district into account and was set as a requirement by the City of Graz and the Austrian Federal State of Styria provided to investors who want to develop the district.

Table 1 provides an overview of the existing heating/cooling sources in the district. Photovoltaic (PV) panels

Table 1 Capacities and temperatures of available heating/cooling sources

Source	Max. capacity [MWh/year]	Temperature at source [°C]	Comments
Marienhütte Stahlwerk medium temperature industrial waste heat	18,000	78	Steel plant with upright waste heat input to district heat and additional potential for more input
Marienhütte Stahlwerk low temperature industrial waste heat	100,000	30	Steel plant with upright waste heat input to district heat and additional potential for more input
STAMAG Malzfabrik low temperature industrial waste heat	1,000	22	Malthouse producing waste heat which may be used for input to heat pumps as well as for cooling
Linde Gas low temperature industrial waste heat	33,000	22	Industrial gases firm producing waste heat which may be used for input to heat pumps as well as for cooling
Cold water well on estates of investor Erber	8,700	10	May be used for input to heat pumps as well as for cooling
PV collectors	1,938	var.	In competition with solar heat for roof space
Solar heat collectors	815	var.	In competition with PV for roof space
District heating system of Graz	no limit defined	var.	District heat provided by the existing heating system of Graz

installed on roofs can supply a total of 1760 MWh/year; however, they compete with thermal solar collectors for roof space. The electricity grid can provide electricity with no practical capacity limit for the district. The natural gas grid is also assumed to cover any load necessary to supply the district. The maximum capacities and temperature levels of the waste heat and renewable energy sources range from 800 to 100,000 MWh/year and from 10 °C to almost 80 °C.

Definition of the maximal energy technology system

Besides quality and limitation of energy sources, the model must also consider seasonal variations in energy demand, in particular for heating and cooling. Respective demands were provided during the project by the Institute of Electrical Power Systems and the Institute of Thermal Engineering of Graz University of Technology and are shown in Figs. 4 and 5 as load functions for heating, cooling, warm water and electricity for the assumed scenarios of building standards for the district. In OIB and NZE standard cases, an electricity demand of 30 GWh/year (excluding electricity for providing heat via heat pumps) is assumed. The entire district requires 45.7 GWh/year of heat (warm water and heating) and 3.2 GWh/year of cooling for the OIB-standard scenario.

For the NZE-standard scenario, the entire heat demand is with 16.6 GWh/year lower than the OIB-standard demand. On the other hand, NZE-buildings need 4.8 GWh/year more energy for cooling.

NZE-standard buildings can reduce heat demand by 63 % however with an increasing demand for cooling in summer (2.5 times more energy compared to OIB-standard) because the different construction needs more ventilation for cooling.

In order to align energy provision with these load profiles, three periods were defined to represent the time-dependent demand of the district. Months with similar energy demand levels were merged to three periods winter, midterm and summer (see Table 2).

The economic framework for the district's development consists of the end-consumer prices and the cost of obtaining energy from different sources and the feed-in tariffs into distribution grids for surplus energy provided in the district. Additional file 1: Table S1 provides energy

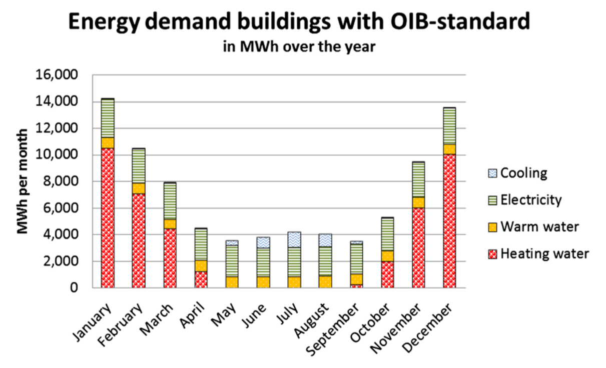

Fig. 4 Load variation over time for the district assuming low energy house standard (OIB) in MWh [53]

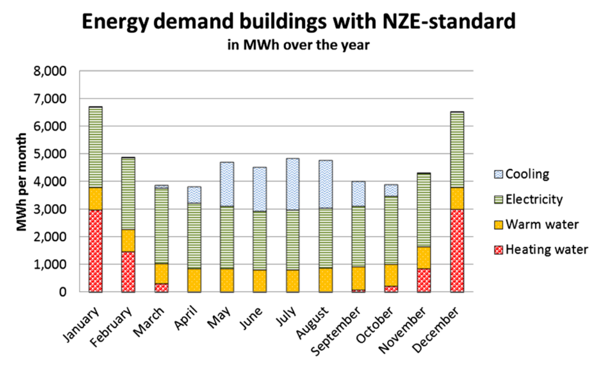

Fig. 5 Load variation over time for the district assuming passive house standard (NZE) in MWh [54]

Table 2 Load periods defined to represent different load situations, all in MWh/year

Period	Months	Hours	Hours in %	Heat demand	Warm water demand	Cooling water demand	Electricity demand
Winter	January, February, November, December	2,880	32.9	33,418	3,213	3	10,892
Midterm	March, April, September, October	2,928	33.4	7,707	3,192	195	9,822
Summer	May, June, July, August	2,952	33.7	12	3,244	3,371	8,780
Year		8,760	100.0	41,137	9,649	3,569	29,495

prices and cost of this economic framework for the baseline scenario NZE. The prices and costs in this table are not fixed but subject to stakeholder negotiations and market price developments. The scenarios provided in the 'Results' section show how changes in this economic framework of prices and costs shape the complex structure of energy provision for the Reininghaus District.

Investment costs of the technologies (taking different sizes of installations into account) as well as costs of grid infrastructure within the district are based on industry information and experiences from other projects. They are summarised in Additional file 1 and remain constant in all scenarios.

There is a large portfolio of technologies that may be applied to provide heating, cooling and electricity for the Reininghaus District. This ranges from simply connecting the group of buildings to existing distribution grids for electricity or heat, to the utilisation of local heat sources to upgrade waste heat with heat pumps, or the collection of solar energy via thermal collectors or PV panels, to name just a few. Many of these technologies can be applied decentrally, meaning at the building site, or centrally, meaning at the site of the source. These options differ by the size of the installations and the distribution system (and distribution losses) as well. Low-temperature waste heat from an industrial source in the form of a water flow can, for example, be the input to a large heat pump at the source, which increases the temperature of the waste heat to the temperature level necessary for residential heating, subsequently distributing hot water via a district heating grid to the buildings. It can, however, also be distributed directly via a grid to the buildings and may locally be upgraded in smaller on-site heat pumps to heat the buildings. Investment costs and distribution losses will vary considerably for these cases and may also vary for different groups of buildings, given the differences in the length of the distribution pipes. This central/decentral option also applies to gas burners and CHP technologies based on gas. Lower prices for coal could influence the optimal energy technology system but a specific barrier to burning solid particles are air-quality restrictions within the city of Graz due to geographically related inversion problems with too high particulate accumulation.

Figure 6 shows the 'maximum technology system' of all suggested technologies used in the model with the exception of distribution grids. These distribution systems connect each sub-quarter with all energy sources available and are modelled in detail. This technology portfolio is the basis for the generation of scenarios provided in the subsequent chapter.

Results

Scenario section

The following describes the scenarios, generated with the PNS based on different economic framework conditions. They provide an example of the broad variation of structures for the energy system for the district, caused by often quite small differences in costs and relative prices of the energy sources in question. The total area of all roofs of the buildings was assumed for three kinds of use: 7 % for solar thermal, 1 % for photovoltaic panels (for energy installation) and 50 % for green planted roofs (for ecological cooling effects), and the remaining 42 % were not open to any purpose. The assumption for energy installations was set on a very low level for the following reasons. On the one hand, climate geographical analysis during the project showed that too much sealing would heat up passing air mass and so further deteriorate the micro-climate in Graz. On the other hand, architectural and constructional characteristic (especially different heights and alignments of buildings cause shadowing effects) as well as the *Dachlandschaftsverordnung* reduce the potential for solar use. This low energy potential was taken in order to be on the safe side with the assumptions.

The time frame for the realisation of the Smart City district Reininghaus is divided into two different segments. A first part consisting of two building blocks (see quarters 1, 4 and 4a in Fig. 3) will be realised within the next years while the remainder of the district will require a longer time to be realised. Therefore, the modelling was also split with one model containing only the two building blocks that will be realised soon and the comprehensive model that includes all building blocks. This arrangement also allows to analyse if the optimum of a subset of buildings leads to qualitatively different solutions than if the whole district is subject to the

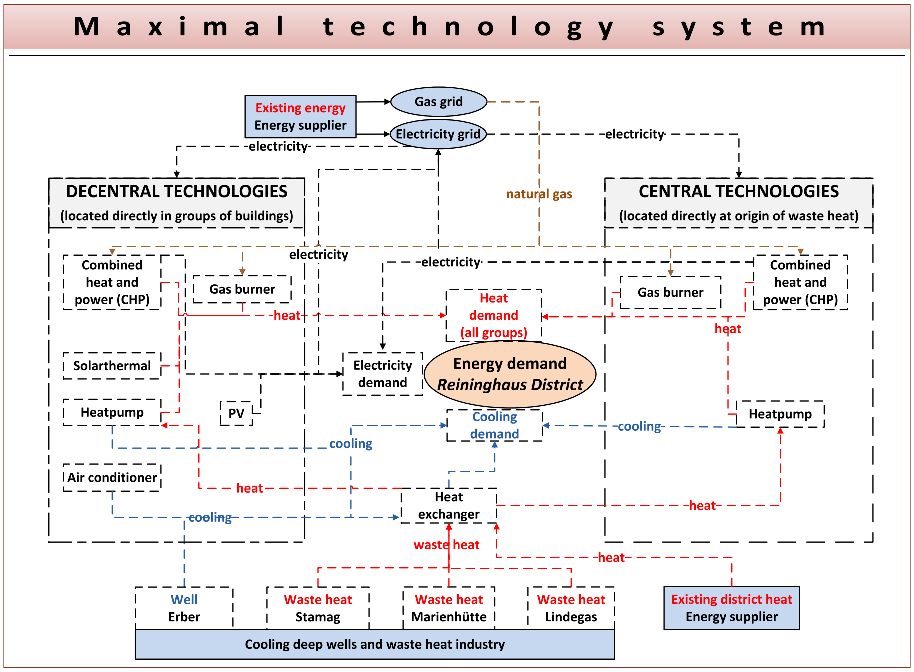

Fig. 6 Maximum technology system for the energy system in detail.

optimum. In all cases, the optimum was carried out for both OIB and NZE standards.

In a last step, the framework of all scenario groups underwent more specific changes. This was important for gaining an overview of how price changes in global market prices or considerations about autonomy and technical changes summarised below would influence the optimal energy technology system. The following parameter classes were defined:

- Identification of sharp cost limits of available waste heat (reducing or increasing actual prices until technology structures start to switch)
- Identification of cost limits for natural gas, existing district heat, cold water well, etc. are not economic anymore (reducing or increasing actual prices until technologies start to switch)
- Autonomous heating and cooling supply options of Reininghaus

Each of the scenarios was also ecologically evaluated with ELAS calculator.

Table 3 describes scenario parameters. Value added per year is in this relation the main output of each optimal scenario and is the result of the total income from selling energy minus the sum of annualised investment cost, operating cost and resource cost. The optimal scenarios were calculated for the case of supplying all quarters of the case study area Reininghaus simultaneously. Results show that value added ranges, depending on changing of parameters, from 245,000 €/year to 641,000 €/year for the whole Reininghaus District and 17,000 €/year to 193,000 €/year for the subset of quarters 1, 4 and 4a. Cost variations were made starting from the basic purchase cost for energy from Additional file 1: Table S1. Prices for selling the energy to the end-consumers were set as fixed market prices.

The following graphs are all based on the maximum technology system as defined in Fig. 6. Sources and technologies that are part of the optimal structure under the designated economic framework are circled. Red circles mean heating, blue circles cooling and green circles identify technologies and sources used for electricity provision in the district. Broken circles represent sources and technologies that are only used for some groups of buildings, or only service a smaller part of the demand, supporting the main sources of energy. The baseline scenario and the scenarios with changed natural gas cost, changed district heat cost and heating autonomy will be shown here in further detail.

Figures 7 and 8 show the energy supply structure for the base line scenario for purchase cost, selling prices and feed-in tariffs defined in Additional file 1: Table S1. The results of these two figures stand for all quarters.

Result overview

These figures show that under current economic conditions, providing heat with decentral natural gas burners in the buildings is optimal, with support from

Table 3 Optimal scenarios with changed side parameters and results

Scenario		Changed parameter		Cost variation (purchase)	Result	
ID	Name	Description	Building standard	Up or down to	Value added per year (all quarters)	Value added per year (quarters 1, 4 and 4a)
0a	Baseline	No additional changes	OIB	–	416,000 €/year	84,000 €/year
0b	Baseline	No additional changes	NZE	–	286,000 €/year	21,000 €/year
1a	Natural gas	Increased^{+}/reduced* natural gas energy price	OIB	€ 57^{+}/€ 47*	358,000 €/year^{+}	91,000 €/year*
1b	Natural gas	Increased^{+}/reduced* natural gas energy price	NZE	€ 51^{+}/€ 45*	259,000 €/year^{+}	24,000 €/year*
2a	District heat	Reduced district heat cost	OIB	€ 51/€ 56	395,000 €/year	74,000 €/year
2b	District heat	Reduced district heat cost	NZE	€ 50/€ 51	270,000 €/year	18,000 €/year
3a	PV	Reduced PV feed-in tariff	OIB	€ 89	375,000 €/year	80,000 €/year
3b	PV	Reduced PV feed-in tariff	NZE	€ 89	245,000 €/year	16,000 €/year
4a	CHP	Increased CHP feed-in tariff	OIB	€ 74/€ 80	424,000 €/year	88,000 €/year
4b	CHP	Increased CHP feed-in tariff	NZE	€ 75/€ 91	316,000 €/year	26,000 €/year
5a	Economic and ecological optimum	No energy cost for purchasing cooling water from deep water well	OIB	€ 0	641,000 €/year	193,000 €/year
5b	Economic and Ecological Optimum	No energy cost for purchasing cooling water from deep water well	NZE	€ 0	525,000 €/year	98,000 €/year
6a	Waste heat limitation	Availability of waste heat just from Marienhütte Stahlwerk	OIB	–	417,000 €/year	74,000 €/year
6b	Waste heat limitation	Availability of waste heat just from Marienhütte Stahlwerk	NZE	–	282,000 €/year	17,000 €/year
7a	Autonomy heat	No external energy for heating	OIB	–	363,000 €/year	85,000 €/year
7b	Autonomy heat	No external energy for heating	NZE	–	261,000 €/year	21,000 €/year
8a	Autonomy heat and electricity	No external energy for heating and electricity	OIB	–	Not possible with just 1 % space on roofs for PV	Not possible with just 1 % space on roofs for PV
8b	Autonomy heat and electricity	No external energy for heating and electricity	NZE	–	Not possible with just 1 % space on roofs for PV	Not possible with just 1 % space on roofs for PV

Energy price purchase cost for energy only without infrastructure cost etc., *€/year* euros/year; *OIB* low energy house standard, *NZE* passive house standard
$^{+}$increased energy price
*decreased energy price

industrial waste heat. In the OIB-standard case (Fig. 7), gas furnaces and high temperature industrial waste heat from the steel plant Marienhütte Stahlwerk share the main burden of heat provision (of which 10 % comes from the industrial waste heat). Low-temperature industrial waste heat from the companies Marienhütte Stahlwerk and STAMAG Malzfabrik provide only a small fraction of the heat demand for quarters close to this source, with the waste heat from Marienhütte Stahlwerk being up-graded in decentralized heat pumps, the STAMAG Malzfabrik waste heat will be used in a central heat pump at the site of the company. Cooling is provided by district cooling from the cold water sources located at the *Erber* estates. Electricity comes mainly from the grid, with local PV contributing 7 % of the demand. The picture is quite similar for the NZE-standard case (Fig. 8), with the exception that the share of the district heat covered by high-temperature waste heat from Marienhütte Stahlwerk is much larger at 30 %. Low-temperature heat from this steel plant will not be used. Cooling now will be provided by de-central air conditioners.

Results of structures for quarters 1, 4 and 4a show the same energy technology network but different amounts of energy described in Table 3.

Figure 9 represents how dramatic changes in the overall structure can become if the cost for a certain source is changed even slightly. A 4 % (NZE-standard) to 16 % (OIB-standard) increase in the gas price will change the supply structure for the NZE-standard case from that given in Fig. 8 to that in Fig. 9. Gas will no longer contribute to supplying heat to the district. It will be replaced by high-temperature industrial waste heat from the Marienhütte Stahlwerk, supported by de-central heat pumps fed by low-temperature waste heat from the Marienhütte Stahlwerk and Linde Gas. In this scenario, solar thermal collectors will also contribute to cover the heat demand,

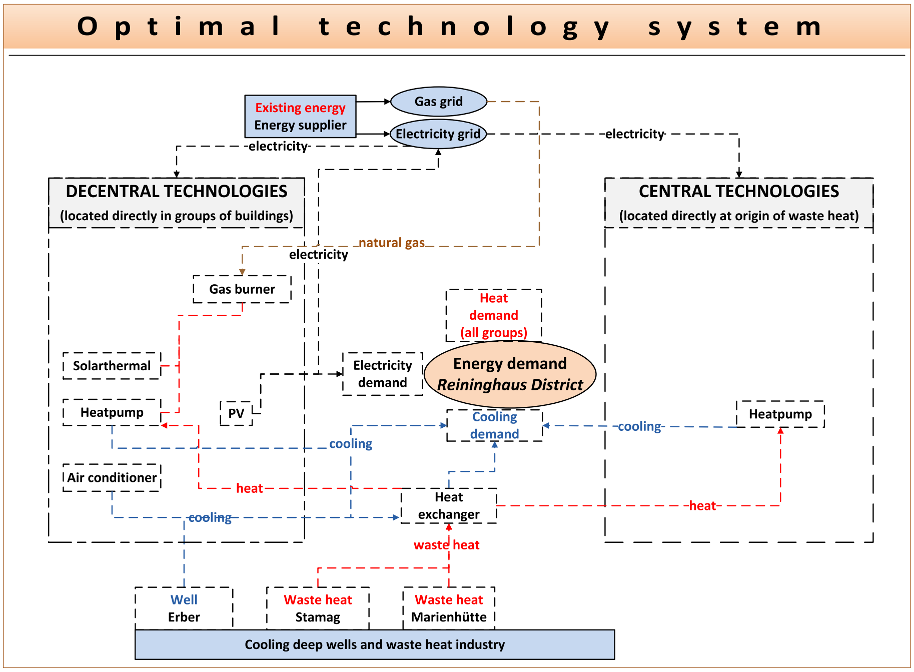

Fig. 7 Optimum energy technology system for base line scenario all quarters (OIB-standard)

reducing the available area for PV panels to supply electricity.

The existing district heating system will only become part of the energy solution for the Reininghaus District if the cost per unit of energy is reduced by approximately 23 % (OIB-standard) to 26 % in the NZE-standard case.

Then, the optimal energy supply structure will change as seen in Fig. 10. Although the main share of heat is still provided by de-centralized gas furnaces, a third of the group of buildings will be connected to the municipal district heating system. Small contributions for buildings close to the sources will be made by high-temperature waste heat from

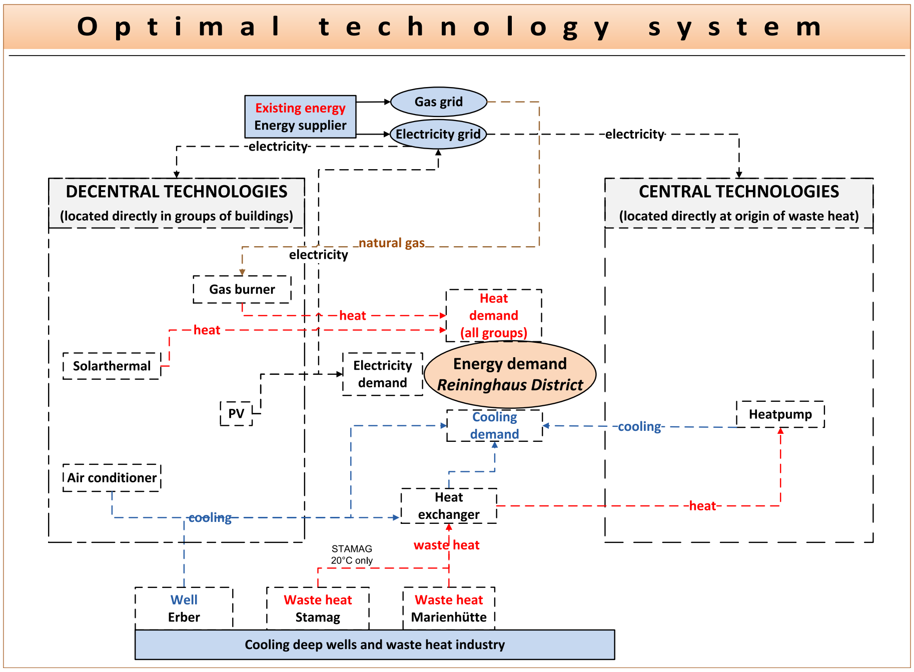

Fig. 8 Optimum energy technology system for base line scenario all quarters (NZE-standard)

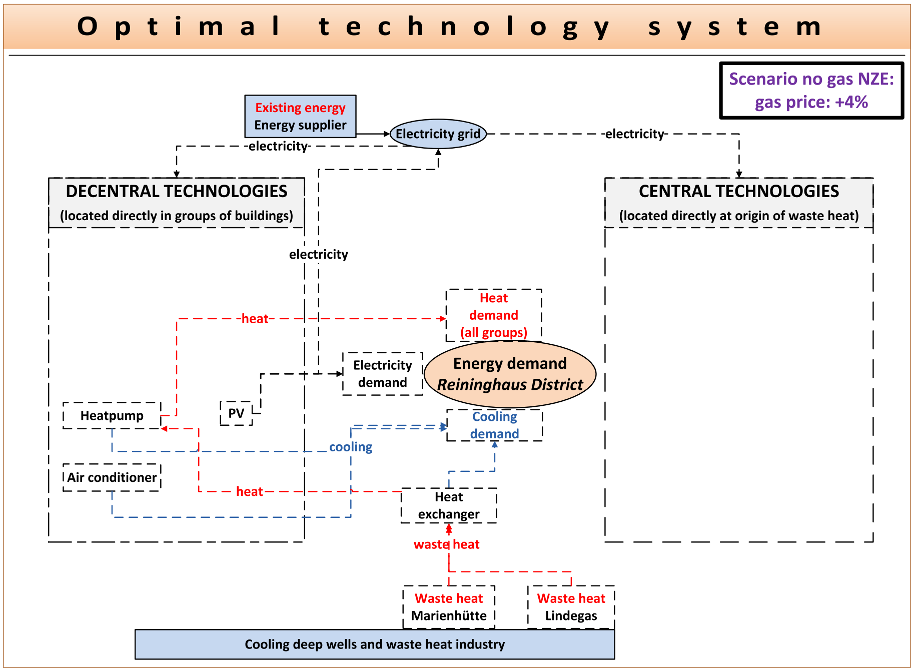

Fig. 9 Optimum energy technology system in the scenario natural gas all quarters with reduced gas price (OIB-standard and NZE-standard case)

the steel plant Marienhütte Stahlwerk and by low-temperature waste heat from Linde Gas, upgraded to a central heat pump at the site of the company.

Finally, the question of only supplying heat and cooling from local sources will be addressed in Fig. 11. Full-energy autonomy is not a viable option for the district, as PV area is restricted to roofs of buildings (even with more intensive area use). This means that under this assumption, it will always be necessary to import electricity. Figure 9 already indicated that the heat load and as

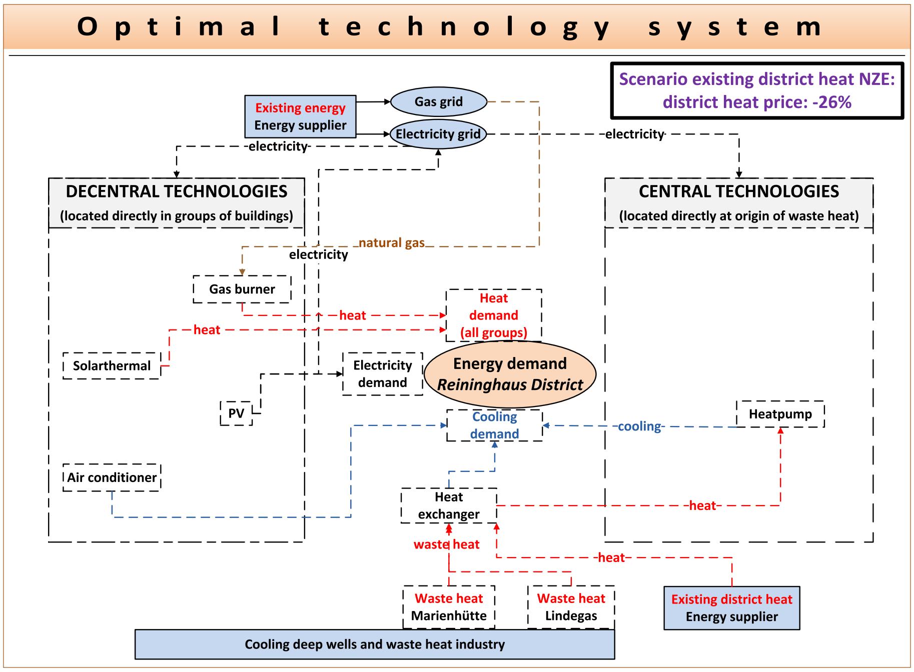

Fig. 10 Optimum energy technology system in the scenario district heat all quarters with reduced district heating cost (OIB-standard and NZE-standard case)

cooling may be supplied by local energy sources only (if electricity is not restricted). Figure 11 shows the most optimal energy system for autonomy regarding heat. In this case, the structures are quite similar for the OIB-standard and NZE-standard case. The main burden of heat supply will be taken by the high-temperature waste heat from the steel plant Marienhütte Stahlwerk, supported by de-central heat pumps fed by low-temperature waste heat from Marienhütte Stahlwerk and Linde Gas. This scenario requires an increase of imported electricity to power the heat pumps. It is interesting that the reduction of profit for this scenario is minor, with 13 % for the OIB-standard case and only 9 % for the NZE-standard case.

Apart from different amounts of energy, described in Table 3, results of structures for quarters 1, 4 and 4a only show different energy technology networks. In this case (as well for OIB-standard as NZE-standard), instead of gas burners, the use of waste heat in combination with decentral heat pumps is the main part of the solution.

Within the optimal scenario where resources, infrastructure (a.o. pipes) and cost/prices are included, marginal prices of resources were calculated. Cost for energy on the local energy market can be tested for volatility. Natural gas becomes uneconomic at a purchase price more than 51 (NZE-standard) or 57 euro (OIB-standard) per MWh, existing district heat becomes economic up to a purchase price of 50 (NZE-standard) and 51 euro (OIB-standard) per MWh (Table 4) and cooling water from deep water wells for cooling processes becomes economic between 37 (NZE-standard) and 41 euro (OIB-standard) per MWh.

High resource costs of waste heat and cooling water favours decentralized technologies. These are primarily natural gas burners, solar thermal plants, heat pumps, photovoltaic systems, air conditioning and to a lesser extent cooling water and waste heat.

The scenario with the highest economic revenue considering both economic performance and low ecological impact leads to a scenario that is completely supplied by the locally available waste heat and cooling water. Total costs of approximately 2.9 million euros per year and product revenue around 3.6 million euros per year can be achieved in this way (Fig. 12). A total revenue of about 0.6 million euros per year could so be created with an optimal energy technology network in the OIB-standard case.

For a yearly-based calculation, the individual life cycle for all energy technologies has been taken into account. The resource cost can exceed investment and operating cost many times over (91 % resource cost of total cost, see Fig. 13).

All scenarios that are generated by optimising economic profit via the PNS model are also evaluated ecologically with the ELAS calculator. The results of this tool provide a broader picture than just the ecological impact of the energy system, also including the life cycle impact (evaluated with SPI) of buildings and urban infrastructure. By replacing fossil fuels with the use of

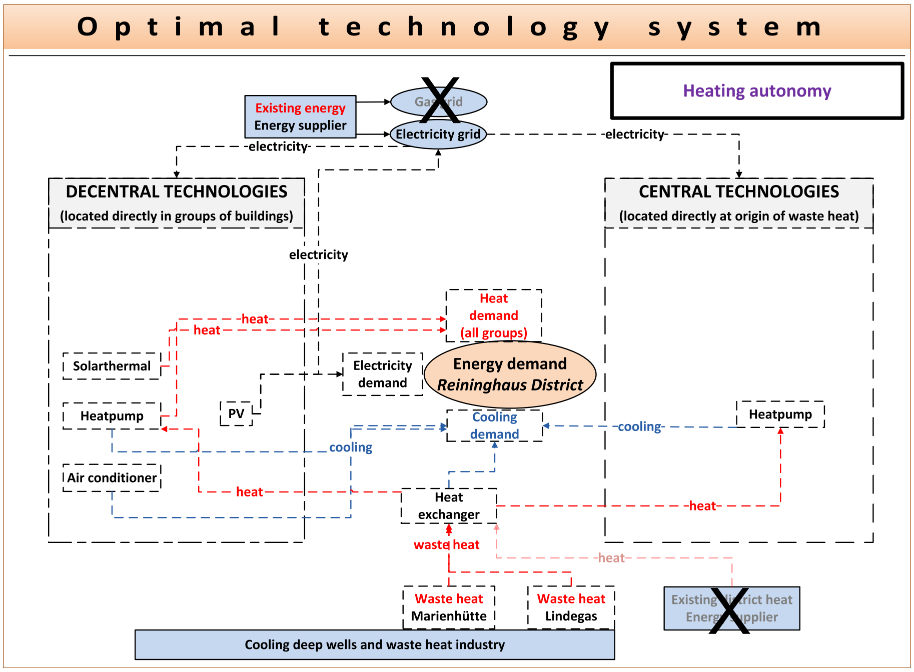

Fig. 11 Optimum energy technology system for scenario heating autonomy all quarters (OIB-standard and NZE-standard case)

Table 4 Examples for stability of resource use OIB and NZE-standard regarding price changes

Purchased energy	Application limit of purchase price level (OIB-standard)	Application limit of purchase price level (NZE-standard)
Natural gas at price level	lower € 57/MWh	Lower € 51/MWh
Existing district heat at price level	lower € 51/MWh	Lower € 50/MWh
Cooling with cold water at price level	lower € 41/MWh	Lower € 37/MWh

waste heat, the environmental pressure decreases in both cases to a very low value compared to electricity (Fig. 14). Electricity remains constant because it is already supplied to a high extent with renewables, and the potential for local electricity production with photovoltaic systems was highly limited because of the respective scenario setting (PV in competition with solar and green biomass on roofs).

Figure 15 provides a comparison of the ecological impact with the part of the energy system highlighted. The baseline optimum scenarios are diagrammed between two extreme scenarios. The advantage of using local waste energy sources is clearly visible by comparing the 'gas free' scenario and the heating autarky scenario with the others. The ecological performance of the NZE and OIB-standard overlap. In comparison to the 110 ha Reininghaus District, the ecological footprint of the OIB-standard is 4000 (100 % waste heat scenario) to 8000 times (100 % natural gas scenario) bigger. For the NZE-standard, it needs 5000 (100 % waste heat scenario) to 6000 (100 % natural gas scenario) times this area.

The electricity demand is covered by the current Austrian mix (78.6 % renewable sources) and cannot be influenced much locally. But the ecological pressure for the heat production can be reduced by more than 60 % as Fig. 16 shows.

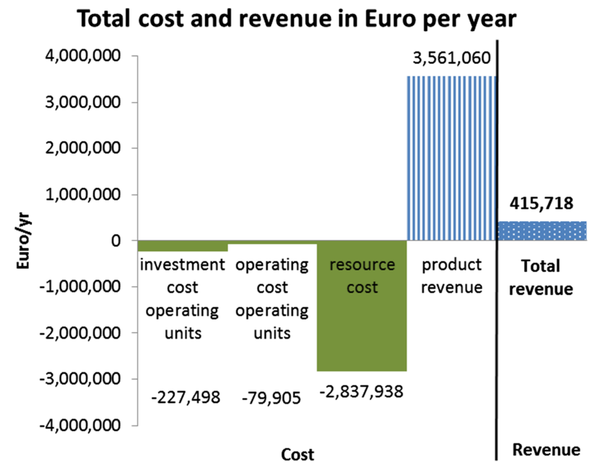

Fig. 12 Total cost and revenue in Euro per year (OIB-standard case)

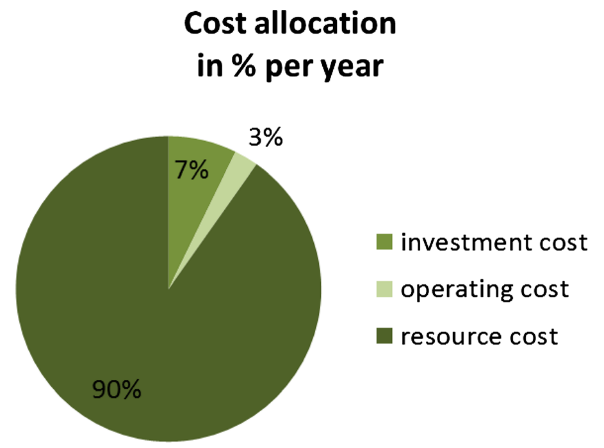

Fig. 13 Cost allocation in % per year (OIB-standard case)

Due to less heat demand, NZE-buildings are already on a much lower level than OIB-buildings (about one third) with corresponding ecological pressure. Independently of the building standards, the substitution of fossil fuels in heat supply can reduce the ecological pressure in both cases.

Energy supply of the Reininghaus District is just a part of the total ecological footprint; therefore, it is suggested that other important factors be discussed further (e.g. mobility). Possible changes of ecological pressure due to heating and cooling (OIB-standard in comparison to NZE-standard) are strongly dependent to the technology network. The existing district heat network of Graz originates from approximately 90 % coal and natural gas supply, which implicates a high ecological pressure. This high value can be reduced if locally available waste heat is used (not including the internal energy demands of the companies Marienhütte Stahlwerk, Linde Gas and STAMAG Malzfabrik themselves). The import dependency on fossil fuels for direct energy supply for building demands can be reduced by almost 100 %.

Discussion

In the search for and planning of a smart economy, optimal energy systems have been found with PNS. Results show that with current prices, decentral natural gas burners supported by industrial waste heat are the economically most feasible energy system. The testing of price variabilities in the scenarios showed that with an increase of the natural gas purchase price (16 % OIB-standard) and a slight increase (4 % NZE-standard), the option of burning gas is no longer a part of the energy system. Instead, an additional use of industrial waste heat in combination with de-central heat pumps is then financially feasible. To become financially feasible, the

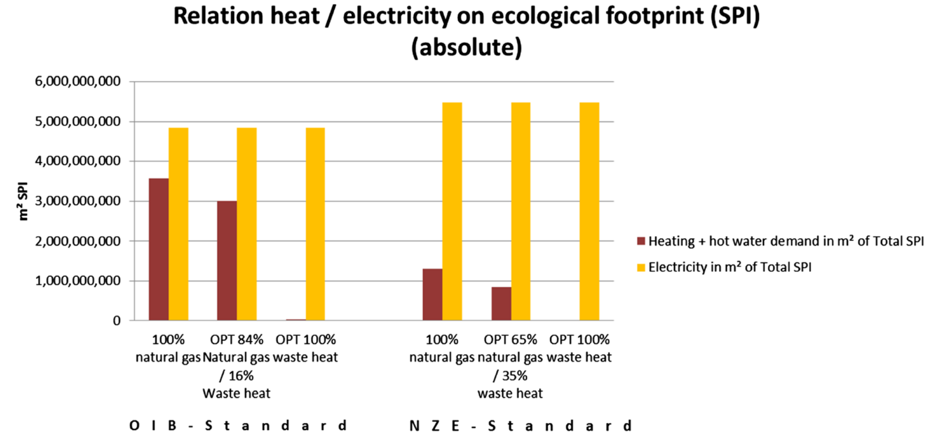

Fig. 14 Comparison of ecological impact of scenarios evaluated with SPI for relation of heat to electricity, using the ELAS calculator (absolute)

district heat purchase price must drop by 9 % in the OIB-standard case and by 26 % in the NZE-standard case, or alternatively, the price of fossils must increase. Depending on further parameters such as density of energy demand, also, solar thermal collectors can become financially feasible. The very cost-intensive energy system of the already existing district heat on location is not financially feasible at the current high price level.

Not less important than the financial issue in the definition of the background section, the need for a *smart* and, as a synonym for a far-reaching concept, a *sustainable* city was mentioned. This implies that an ecological evaluation of the discussed scenarios of energy technology systems can be supportive in the discussion and scaling of a well-balanced socio-ecological economic process.

After the process optimisation and the ecological evaluation, resource, financial and ecological aspects were overlapped to find the scenario which is most ecologically friendly at the lowest costs. In this consideration, decentralised systems with low temperature waste heat and decentralised heat pumps show the financially most feasible (revenue more than 640,000 €/year) and, compared to alternatives, most ecological way (more than 60 % reduction potential of the ecological pressures of heat) to supply the new quarter. This scenario has the highest financial revenue when energy cost for purchasing the cooling water at 10 °C from deep water wells is available at very low costs. This seemed to be a realistic option due to the fact that the investor and owner of the deep water wells was interested in independent implementation alternatives to provide a decentral energy system solution. A use of the local waste heat can reduce import dependency on fossil fuels by almost 100 % of the final energy consumption.

The general planning process for the Reininghaus District is still in progress. The scenario results were used to inform the involved stakeholders about how the

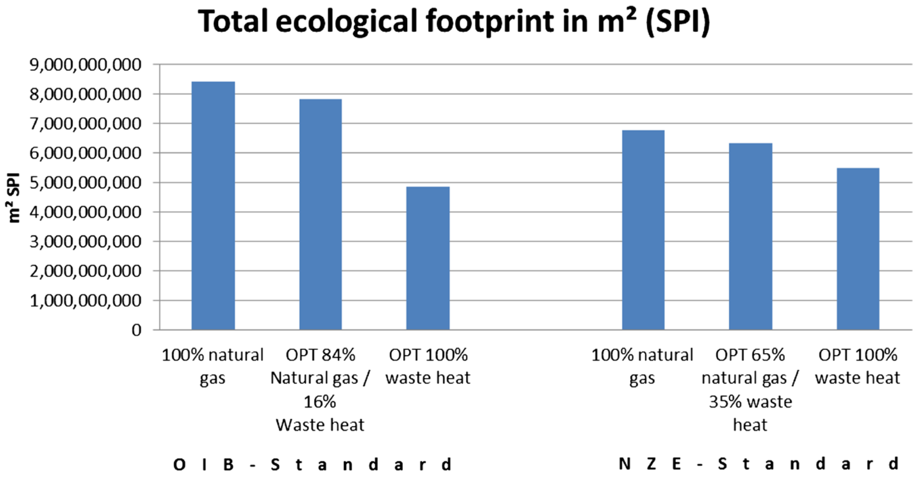

Fig. 15 Comparison of total ecological impact of scenarios evaluated with SPI, using the ELAS calculator

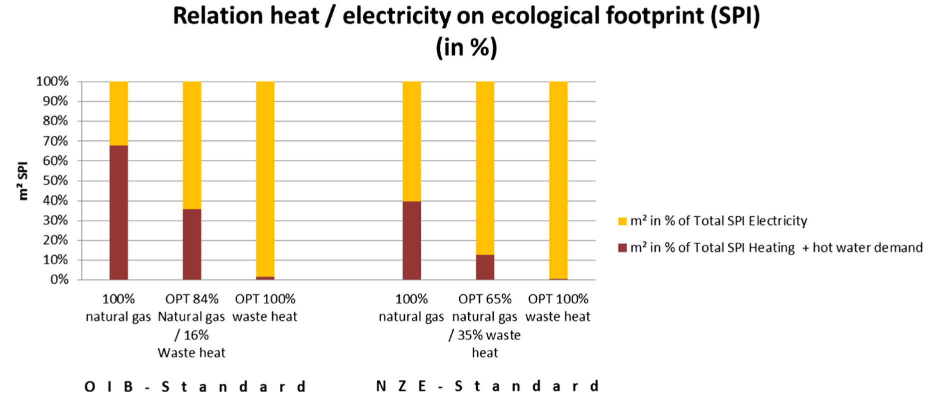

Fig. 16 Comparison of ecological impact of scenarios evaluated with SPI for relation of heat to electricity, using the ELAS calculator (in %)

ecological footprint could potentially be reduced and how financial issues of different developments of energy prices and energy technology supply options could be handled. This basic research about ecological aspects of optimal energy technology supply for the Reininghaus District further was compiled with other information collected in the project from project partners. This information consists of analyses concerning microclimate, city planning, construction materials and further modelling of concrete scenarios for the spatial planning and energy supply of the Reininghaus District. The framework energy plan City Graz Reininghaus can now evolve into a comprehensive guideline for an integrated city planning.

This work did not cover all discussed sustainable city or smart city aspects since it laid the focus on the application of the described methodology for the use in urban energy planning and environmental sustainability concepts. In this case, the field of application of the discussed methodology can be described as a top-down smart city approach initiated by institutions of all administrative levels of the state (municipality, province and federal ministry) and research facilities. From the perspective of a general smart city concept categorised into six smart city functions, the discussed methodology mainly considered the smart economy and smart environment functions.

However, it allowed to model the specific local context of a city quarter considering many factors in relation to urban energy planning like, e.g. available concerning energy consumption, available local and imported resources, energy standards, existing infrastructure, local stakeholder interventions, etc. Most of them were mentioned as keywords in the smart city actors matrix in the ‘Background’ section. With this contextual setting, the financial feasibility of well-established technologies could be identified by testing the elasticities of energy cost.

Applying PNS for resource and technology systems for the energy supply of city districts helped to discover optimal energy systems out of a setting of complex supply and demand options. In the case of the smart city district Reininghaus, Process Network Synthesis has been applied to guarantee that only optimal scenarios representing different economic boundary conditions considering cost variations for energy services and energy sources are compared.

The results of the scenario generation with the PNS method show that even small changes in the setup of the price/cost structure for cooling, heating and electricity can cause dramatic differences in the optimal energy system to supply a smart city district. Shifts between fossil and renewable systems already happen when cost for natural gas rise slightly (NZE-standard case). A shift to an integration of heat from the existing district heat system would need a significant reduction of the price for district heat. Integrating industrial waste heat may allow to cover the heat demand for buildings with NZE-standard and even OIB-standard with local sources at reasonable economic cost. Electricity supply however cannot be covered within the restriction of only applying PV panels on rooftops.

Conclusions

Besides the economic optimum, ecological performance is a major issue in planning smart cities. A comparison of the ecologic life cycle performance, including construction and operation of buildings as well as urban infrastructure and mobility, clearly indicates that energy plays a key role in the ecological impact of settlements. Using the comprehensive evaluation method of Sustainable Process Index (integrated in the ELAS-calculator), roughly two thirds of the ecological impact in the case of a smart city district within a middle-sized city can be attributed to different forms of energy supply (most of it for domestic heat purposes). Using local energy sources instead of imported fossil fuels, in particular industrial waste heat, can considerably reduce the ecological impact. In addition, this exposes a potential to stimulate regional value creation when reducing the import dependency on fossil fuels.

Applying the selected methods could provide useful information to give some answers to the challenges and research questions posed in the beginning of this case study. An integration of available local energy sources into an optimal energy system in order to meet future energy demands could be discussed with the generation of scenarios for a new development of a city district. These scenarios contain optimal solutions for energy systems considering resource limits and expectable changes of market prices. The analysis of settlement structures of the scenarios helped to find out the impact level for each energy system option from an ecological point of view. An energy system solution could be found with the lowest ecological impact and the highest financial revenue.

Additional file

Additional file 1: Cost and technology data. (DOCX 50 kb)

Abbreviations

°C, degrees Celsius; CHP, combined heat and power; €/year, currency of European Euros per year; ELAS, Energetic Long-term Analysis of Settlement Structures; Erber, investor, owning the estates where water wells are located in Reininghaus; GWh, gigawatt hours; GWh/year, gigawatt hours per year; ICT, information and communication technology; ID, identification number; kWh, kilowatt hour; Linde Gas, company for gas products; Marienhütte Stahlwerk, name of an industrial steel company; MWh, megawatt hour(s); MWh/year, megawatt hour(s) per year; NGO, non-governmental organisation; NZE-standard, Nearly Zero Emission standard (In the interest to guarantee a better readability in this work, the phrase 'NZE-standard' will be consistently used. To avoid misunderstandings, each part of the phrase is connected by a hyphen.); OIB-standard, Oesterreichisches Institut für Bautechnik (Austrian Institute for Construction Engineering), compulsory building standards (In the interest to guarantee a better readability in this work, the phrase 'OIB-standard' will be consistently used. To avoid misunderstandings, each part of the phrase is connected by a hyphen.); OEROK, Austrian Conference on Spatial Planning/Oesterreichische Raumordnungskonferenz; PNS, process network synthesis; PV, photovoltaic; STAMAG Malzfabrik, Stadtlauer Malzfabrik Aktiengesellschaft (malthouse); var., various

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Author's contributions

The author has contributed to the Smart City project Energy City Graz Reininghaus. SM has written, read and approved the manuscript.

Author's information

SM, born in 1983 in St. Andrä, Austria graduated in environmental system sciences from the University of Graz. He is currently working at the Institute for Process and Particle Engineering, Graz University of Technology. His research is focused on energy technology system optimisation in regions and rural and urban areas, holistic urban energy system planning and ecological evaluation.

Competing interests

The author declares that he has no competing interests.

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