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Developing a locally balanced energy system for an existing neighbourhood, using the 'Smart Urban Isle' approach

Sabine Jansen ^{*}, Saleh Mohammadi, Regina Bokel

Delft University of Technology, Faculty of Architecture and the Built Environment, Julianalaan 134, 2628 BL Delft, the Netherlands

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ABSTRACT

This paper describes a step-by-step approach for generating various energy concepts for neighbourhoods, based on local renewable resources. The approach is developed within the European research project 'Smart Urban Isle' (SUI). While much literature is focussed on comparison or optimization of predefined configurations, the SUI approach adds to the existing knowledge by introducing a systematic step-by-step approach that supports the first step of the development phase, i.e., the generation of various - potentially innovative - energy system configurations for neighbourhoods, which in the following phase can be optimized using optimization methods.

First, the five steps of the approach are introduced, and secondly, these are applied to an existing residential neighbourhood in the Netherlands. The resulting preferred energy concept for the case study consists of a local, ultra-low temperature heat grid, heated by decentralised heat production from PV-thermal (PVT) collectors on individual roofs and connected to a collective seasonal underground storage (ATES).

This paper demonstrates the usefulness of the approach for generating various alternative innovative energy concepts for neighbourhoods, based on the local demands and energy potentials, and also describes the resulting energy concept developed for the case study. This innovative energy concept can also be applied to similar residential neighbourhoods.

1. Introduction

1.1. Background

The transition towards CO₂ neutral and renewable energy systems for the built environment is essential to prevent further climate change and fossil fuel depletion. In Europe, 79 % of the final energy use in households consists of heating, while 75 % of the heating and cooling demands are produced by fossil fuels (European Commission, 2020). Hence, sustainable energy systems for heating and cooling in buildings, neighbourhoods, and cities are needed.

In order to supply all our energy needs with sustainable resources, we cannot only rely on increased energy production from sustainable resources; also, the reduction of the energy needed for our systems is a key part of the solution. Without reducing our (final) energy consumption, we will not be able to fulfil all our needs with renewable sources (Singer, 2011), nor sufficiently reduce CO₂ to meet the climate goals (Rogelj et al., 2018).

Energy systems for the built environment can be regarded at

different scales: from individual building solutions to large-scale centralised solutions. Traditional energy systems are based on large-scale centralised supply of electricity and often gas or district heating. Currently, more attention is being paid to neighbourhood and district scales, since more renewable energy is available locally. In addition, at neighbourhood scale, there are more opportunities to reduce the system energy input than at building scale, as there is more potential for the exchange of energy between buildings and much can be gained by sharing optimally sized local storage or energy generation components (Ala-Juusela, Crosbie, & Hukkalainen, 2016; Jank, 2017; von Wirth, Gislason, & Seidl, 2018; Walker, Labeodan, Maassen, & Zeiler, 2017).

The European research project 'Smart Urban Isle' (SUI) (Smart Urban Isle, 2018), therefore, aimed at developing neighbourhood energy systems that locally balance the energy system as much as possible: the required energy is generated, exchanged and stored in the area. A systematic approach for developing neighbourhood energy systems was one of the goals of the SUI project.

The SUI project was carried out by seven different countries in Europe and included several case studies. This paper describes the

^{*} Corresponding author.

E-mail address: S.c.jansen@tudelft.nl (S. Jansen).

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energy system development for the case study ‘Ramplaankwartier’, an existing residential neighbourhood in Haarlem, the Netherlands, using the approach developed within the project. This paper demonstrates the usefulness of this approach for developing innovative, locally balanced energy systems and concludes with the resulting innovative energy concept. This innovative energy concept can also be applied to similar residential neighbourhoods.

1.2. Literature review on a neighbourhood energy system development

Numerous papers can be found on sustainable or efficient energy systems for the built environment, ranging from building level to large-scale energy system design. A brief overview on this topic is provided as the first part of the literature review. As the SUI approach aims at energy system design at a neighbourhood scale, the second part of the review is narrowed down to papers on this topic: the development and design of sustainable energy configurations at neighbourhood scale.

1.2.1. Brief overview of literature on efficient energy systems for the built environment

The energy efficiency of buildings has gained attention since the 1970's (Papadopoulos, 2016), and many studies have been conducted on this topic even since. Pacheco, Ordóñez, and Martínez (2012) present an extensive literature review on energy efficient building design. Also, several studies can be found on smart energy retrofitting of buildings (e.g. (Hashempour, Taherkhani, & Mahdikhani, 2020; van den Brom, Meijer, & Visscher, 2019).), as well as on highly efficient building energy systems, (e.g. (Jansen, 2013; Schmidt et al., 2017a)). In 2010, the recast of the European Energy Performance Directive (EPBD) (European Union, 2010) has introduced the nearly zero energy building concept aiming for buildings with zero or very low energy demand, which in addition should be covered to a very significant extent by energy from renewable sources, produced on-site or nearby.

Related to energy systems at larger scale, many publications can be found on the development from centralised (national) energy systems to more local and distributed systems, as a result of more renewable and thereby more local energy generation. Many of these publications focus on distributed electricity production and smart electricity grids, such as for example (Fraser, 2002; Veldhuis, Leach, & Yang, 2018). However, also other energy carriers and sources can be included in distributed energy systems, as described by Allanne and Saari. (Allanne & Saari, 2006), who provide an overview of and discussion on the definition of distributed energy systems (DES). According to these authors, a DES refers to a system in which energy conversion and generation are located close to the end-user. They conclude that DES has great potential to increase the sustainability of the energy supply to buildings. As described in the introduction and also mentioned by several authors, i.a. (Ala-Juusela et al., 2016; Jank, 2017), the neighbourhood scale offers great potential to optimize energy systems.

1.2.2. Development and design of sustainable energy configurations at neighbourhood scale

The SUI approach aims at energy system design at a neighbourhood scale. Therefore, this part of the literature review is narrowed down to papers on this topic: the development and design of sustainable energy configurations at neighbourhood scale.

Bejan et al. (Bejan, Tsatsaronis, & Moran, 1996) describe the design process of (thermal) energy systems as consisting of the following steps: 1) Understanding the Problem; 2) Concept Generation; 3) Detailed Design; 4) Project Engineering; 5) Service. The step ‘Concept Generation’ involves creativity to generate various alternative solutions to the problem and an initial screening of potentially optimal solutions. According to these authors, it is an essential step: “Since the methods of engineering analysis and optimization can only polish specific solutions, it is essential that alternatives be generated having sufficient quality to merit polishing”.

Only few papers were found that mention ‘development’ or ‘design’ in combination with keywords related to ‘energy system’ and to urban energy systems (neighbourhood, built environment, building) (Akbari, Jolai, & Ghaderi, 2016; Mehleri, Sarimveis, Markatos, & Papageorgiou, 2012; Quan, 2017, 2019). Also these papers however focus more on the optimization of designs rather than the generation of significantly different alternatives. Akhbari et al. (Akbari et al., 2016) describe an optimization model applied to a predefined energy configuration, including many optimization parameters within this scheme. The papers of Quan (2019, 2017) describe a parametric design of the building geometry within a neighbourhood, which, if sufficient freedom is given to the variations of the parameters, can lead to the generation of truly different design solutions for the building geometry. Mehleri et al. (2012) present a method to mathematically select the optimal combination of energy system components for a neighbourhood, among several predefined optional technologies. Hence, these papers are focussed on optimisation methods; the actual generation of fundamentally different energy configurations is not the topic of these papers.

It was concluded that papers related to the design of neighbourhood mainly focus on other parts of the design process than the concept generation phase. The following topics were identified to be often found in the related literature: 1. methods and approaches for identifying local energy potentials; 2. comparative analyses of local energy concepts, 3. performance indicators, 4. optimization methods, and finally, 5. non-technical aspects. The first topic (local energy potentials) can be considered as part of step 1 “Understanding the Problem”. Aspects 2, 3, and 4 can be considered as part of the screening and evaluation of alternative concepts and of step 3 “detailed design” according to Bejan et al. (1996). Non-technical aspects are very relevant for the overall process but also do not focus on the generation of alternative technical system solutions.

Below, the review of papers according to the above mentioned categorisation is presented. The review described below does not aim to be exhaustive but presents relevant papers on each topic.

- 1 Identifying local energy potentials: The energy potential mapping (EPM) method developed by Van den Dobbelsteen focusses on identifying and quantifying local renewable potentials, with the aim to make optimal use of these in local energy systems (Broersma, Fremouw, & Van Den Dobbelsteen, 2013; Van Den Dobbelsteen, Jansen, Van Timmeren, & Roggema, 2020). EPM studies are often applied to urban or regional scales, but can also be applied at the neighbourhood scale (van den Dobbelsteen, Broersma, & Stremke, 2011).
- 2 A comparative analysis of local energy concepts is presented by Jansen, Bokel, Elswijk, and Müller (2016), comparing four different energy systems for a new built area in Amsterdam. Also, in Schmidt et al., (Schmidt et al., 2017b) the comparison of different configurations for a new neighbourhood is described. In both papers, various centralised and decentralised configurations are compared and evaluated on annual heating costs and several other performance indicators.
- 3 Crucial to the comparative analysis are the definitions of the performance indicators. Ala Juusela et al. (Ala-Juusela et al., 2016) present definitions of energy positive neighbourhoods. They go beyond simple energy neutrality and include performance indicators for local energy balance, mismatch between demand and supply, and a holistic view on the sustainability of a certain energy system, for example, by including transport of imported energy sources.
- 4 Optimization of neighbourhood energy systems is extensively studied. Some examples are mentioned below. In Bejan et al. (1996) the difference between design and optimization is explained. Design refers to the phase where various alternative solutions or configurations are generated that can meet the project requirements. These alternative solutions can be screened and the best one(s) selected for further development and optimization. Hence, optimization can only

be performed on defined (conceptual) designs, while during the first design phase, alternative solutions are generated. Application of mathematical optimization models to neighbourhood energy systems is the focus of the research presented by Weber, Marechal, and Favrat (2007) and Mehleri et al. (2012), where they apply complex mathematical models to find optimal sizing and configurations of various optional energy components in a neighbourhood energy system. Optimization is also often part of an energy hub approach, which can be applied to neighbourhood energy configurations as well (Mohammadi et al., 2018; Orehounig, Evins, & Dorer, 2015).

5 In addition to the above, mainly technical aspects, various papers can be found on less technical issues such as the local energy planning (e.g. (Leal & Azevedo, 2016; Neves, Leal, & Lourenço, 2015)), stakeholder management and participation (e.g. (Hettinga, Nijkamp, & Scholten, 2018; Lufkin, Rey, & Erkman, 2016; Van Der Schoor & Scholtens, 2015)) and social acceptance (von Wirth et al., 2018). Many papers can be found on local energy planning, mostly focussing on local authorities and how they can achieve the climate goals. The planning process described by Neves et al. (2015) also includes the step of generating alternatives (step V) to meet the (greenhouse gas) reduction goals. Their approach is based on selecting and combining items from a large catalogue of potential measures. The original catalogue of measures is not available, but from the examples it can be seen that measures for various sectors are included. As mentioned in their paper, a challenge of this approach is to assess to what extent measures can be combined and the reported energy impacts can be simply summed up. Since this method is based on selecting measures from various sectors, it is not focussed on generating integrated neighbourhood energy concepts. Furthermore, various papers on stakeholder management can be found. Stakeholder engagement is regarded an important aspects in energy planning for a neighbourhood, and according to Hettinga et al. ((Hettinga et al., 2018) stakeholders can play a role not only in decision making, but also come up with ideas for their neighbourhood. In this sense, they can play a role in the creative process of generating alternative solutions, as well as the evaluation process. Hence, in these papers the aspect of generating alternative energy plans is included, but they do not offer a method for the systematic generation of integrated alternative solutions for neighbourhood energy systems.

Summarizing, it can be concluded that an extensive number of papers can be found on the topic energy-efficient building design as well as on distributed and local energy systems, while a much smaller amount of papers were found that deal with neighbourhood energy system design. Of these, no papers were found that focus specifically on the phase of generating alternative solutions for neighbourhood energy systems. As part of a total energy planning process, the phases 'generation of alternatives' (Neves et al., 2015) or 'generation of ideas' (Hettinga et al., 2018) were mentioned, but these approaches were not aimed at developing integrated neighbourhood energy configurations. Various papers can be found that study other parts of this design process, such as mapping local energy potentials (Energy potential mapping), comparison of alternatives and performance indicators, and optimization models. Many papers also investigate social issues related to the neighbourhood energy system.

Hence, the SUI approach described in this paper is adding to this knowledge by focussing on the phase of generating alternative solutions for an integrated and potentially innovative neighbourhood energy system. The structured step by step approach includes many of the aspects found in the literature (i.e., analysing local potentials and applying performance indicators), but focusses on the generation of alternative energy configurations.

1.3. Paper outline

In Section 2 of this paper, a short introduction to the Smart Urban Isle

(SUI) project is presented and the SUI approach for generating neighbourhood energy system concepts is explained. Sections 3 presents the application of the SUI approach to the case study, resulting in a novel neighbourhood energy configuration. Conclusion and recommendations can be found in Sections 4 and 5.

2. The Smart Urban Isle (SUI) approach

2.1. Introduction to the smart urban isle project

The 'Smart Urban Isle' (SUI) project is a JPI Urban Europe project, with partners from Spain, Austria, Cyprus, Romania, Switzerland, Turkey and the Netherlands. A 'Smart Urban Isle' is defined as 'an area around a (public) building that locally balances the energy as much as possible, resulting in minimized import of energy from outside this area' (Smart Urban Isle, 2018). More general, a smart urban isle is an urban area with a smart local energy system that minimizes the need for external energy. The aim of the project was to support the development of these kind of 'urban isles', by developing smart energy systems that make better use of local resources, that integrate and optimize the bioclimatic design of buildings and related energy patterns, and make use of the scale advantages of connecting more buildings in a neighbourhood.

The project consists of three complementary research blocks: (1) bioclimatic design, (2) management platform and (3) mini-networks. Bioclimatic design aims at maximum comfort inside the buildings with minimum energy input. The management platform deals with the automatic active measures that can be taken up in the SUI area. The SUI mini-networks block focusses on the development of local area energy concepts, investigating how to facilitate the generation, storage, and supply of energy in the SUI area. In this paper, the focus is on the application of block 3 'mini networks'. For this block, the SUI approach was developed to support the first phase of the energy system design process, i.e. the generation of various alternative energy network configurations.

2.2. Overview of the SUI approach for developing locally balanced urban energy systems

As described in the literature review, the SUI approach adds to the existing knowledge by introducing a systematic step-by-step approach that supports generation of various integrated energy system configurations for neighbourhoods. The steps of the approach include several of the aspects and methods mentioned in the literature review, such as the setting of KPI's and energy potential mapping. After this concept generation phase, further optimization of the promising concepts can be carried out, as explained in the literature review.

The SUI approach consists of 5 steps, as shown in Table 1: 1) The overall description of the case study area for which the concept needs to be developed; 2) Investigation of the energy status quo, being the starting point of the analysis; 3) An inventory of energy potentials, exploring (a) the bioclimatic potential (energy saving potential of all buildings), (b) the exchange potential (exchange of heating and cooling of different functions within the area), and (c) the energy that could be generated in the area from local renewable resources; 4) The actual generation of alternative solutions, based on the investigations of the previous steps; 5) the evaluation and selection of the most promising alternative.

The steps are summarised in Table 1 and further explained in the related subsections below. In Section 3 they are applied to the case study. In Section 2.3 some essential definitions on the energy system are provided.

2.3. The energy chain: energy demand, final energy and primary energy

For understanding and evaluating energy systems, the energy flows

Table 1

SUI Guidelines for developing locally balanced neighbourhood energy concepts, as also described in (Jansen et al., 2018a).

Steps:	Goal	Results
1. SUI description & KPI's a) Site description b) Buildings c) Context d) KPI's	to define the project area, site characteristics, describe buildings and infrastructure and select Key Performance Indicators (KPI's).	1.1 Site characteristics 1.2 Overview of existing and planned buildings & infrastructure 1.3 Context and boundaries 1.4 Selected KPI's
2. Energy status quo: a) Existing energy infrastructure b) Energy demand c) Current energy supply	to provide an overview of the status quo of the current energy system. For new buildings a reference situation based on requirements can be defined.	2.1 Existing energy infrastructure 2.2 Current energy demand 2.3 Current local renewable energy supply
3. SUI concept potentials a) SUI Bioclimatic improvement potential b) SUI energy exchange c) SUI renewables potential	to determine all energy potentials: potential reduction of the demand, exchange between different functions and renewable supply using different technologies.	3.1 Quantified demand for various building solutions 3.2 Potential energy exchange 3.3 Energy potential of local resources
4. SUI concept development a) Connecting demand and supply potentials b) Heating and cooling options c) Electricity supply options	to develop energy configurations that meet the demand with maximised use of local energy potential, in order to evaluate the preferred option in step 5.	4.1 Schemes of the different energy configurations that can meet the demand 4.2 Energy balances of the configurations
5. Evaluation & selection	to quantify the performance and evaluate the KPI's for the different solutions developed in step 4	5.1 KPI's of each concept 5.2 Selection of 1 or 2 promising SUI solutions for further development

can be determined on three different levels of the energy supply chain: Energy demand, final energy, and primary energy. The energy chain is shown in Fig. 1.

The different levels are defined as follows:

- The energy demand for heating and cooling is defined in the European norm for energy performance of buildings (EN/ISO 13790, 2008) as 'the heat to be delivered to, or extracted from, a conditioned space to maintain the intended temperature conditions during a given period of time'. This demand is caused by the building

properties, outdoor weather conditions and user requirements. The energy demand is thus mainly an indicator of the building properties and is independent of the applied technical systems. The energy demand is delivered by the building energy system – consisting i.a. of the emission system such as radiators and the heating device, such as a boiler or a heat pump - which requires an input of energy.

- Final energy is the energy in the form of an energy carrier (gas, electricity, or heat) bought at the meter; it is defined by Eurostat as 'the energy consumed by end-users', such as households (Eurostat, 2019). The final energy is thus the energy needed by the technical systems in the building and the amount of final energy used is therefore also determined by the efficiencies of these systems.
- Final energy is in turn delivered by the national or regional grid. It is nationally produced by components such as power plants or wind-mills, which need an input of primary energy. The European Committee for Standardisation (CEN, 2012) defines primary energy as 'energy that has not been subjected to any conversion or transformation process'. In principle, the primary energy includes both fossil and renewable sources. However, in the determination of the national primary energy factors (PEF) it is not always clear how renewables are assessed, as explained by Molenbroek, Stricker, and Boermans (2011).

When going through the steps of the SUI approach, it is important to clearly define to which level the energy use of a building or neighbourhood is related.

2.4. Step 1: SUI description and KPI's

2.4.1. Case study description

In step 1 an inventory of the area is carried out, including identification of the spatial boundaries of the SUI and basic data concerning location (latitude, longitude, and altitude), area characteristics (local climate, land type, and urban location) and an inventory of existing buildings (building density, population, numbers, and types of buildings). The climate classification can be based on Koppen Geiger (Beck et al., 2018), but local climate statistics can also be used.

2.4.2. KPI's for the Smart Urban Isle project

Since the aim of the project is to achieve local energy balance and minimize external input, the following four standard Key Performance Indicators are defined in the SUI project: Local renewability fraction, fraction of autonomy, net import of energy, and annual CO₂ emissions of the net energy imported from outside the project area. These are shown in the scheme of Fig. 2. The sub-indicators on the left can be used for

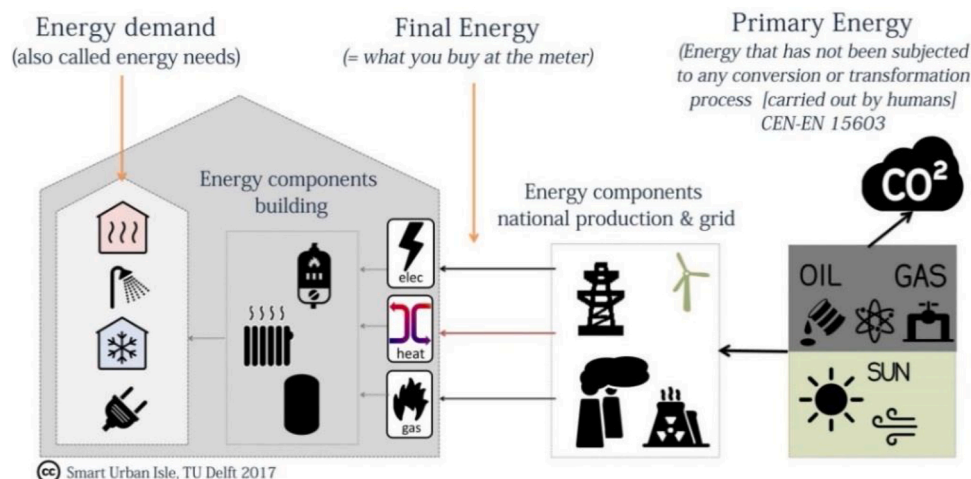


Fig. 1. Energy chain: demand, final energy and primary energy.

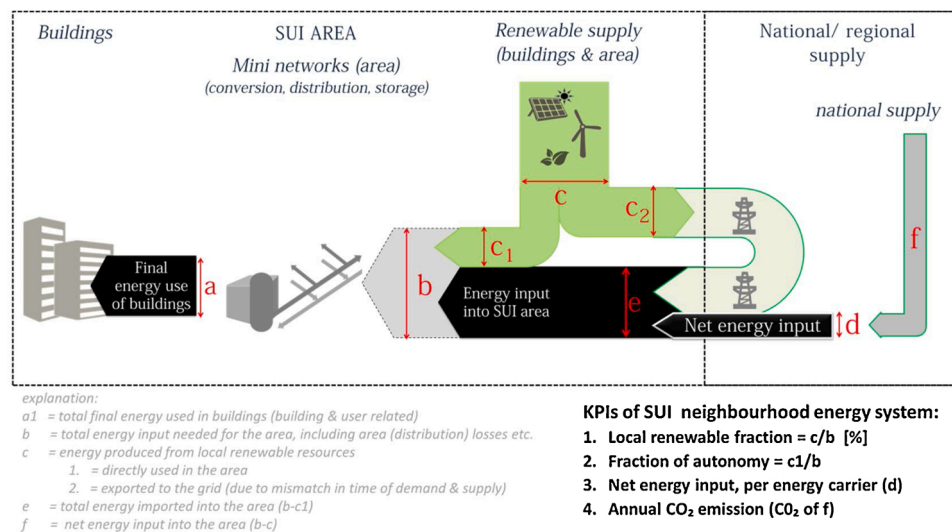


Fig. 2. Scheme of the Key Performance Indicators used.

more insight into the system.

2.5. Step 2: energy status quo

Step 2 involves the inventory of current energy infrastructure, energy use, and renewable generation. When identifying the current energy ‘use’ it must be clear which level of the energy chain is presented (demand, final energy, or primary energy), as explained in Section 2.3. Often, some conversion between these is necessary.

For existing neighbourhoods, the final energy consumption can in principle be obtained from the grid operators. If no measured final energy data are available, national reference numbers can be used, preferably based on building characteristics such as year of construction, energy performance certificate or energy label, in line with the European Energy Performance of Buildings Directive (European Union 2010). Also, energy performance calculation methods can be used to estimate the net heating and cooling demand and the energy performance (EN/ISO 13790, 2008), but it has to be noted that significant differences can occur between calculated and actual energy performance (Majcen, 2016).

After determining the (final) energy consumption, the division between the different energy types - heating, hot water, cooking, cooling, lighting, and other electricity use - should be determined.

Finally, as most real data is provided based on ‘final energy’ consumption, this number must be converted to energy demand or needs (see Section 2.3). The energy needs are the basis for the energy-saving potentials as well as the new to be developed (building) energy system. In Section 3, this is demonstrated for the case study.

2.6. Step 3: SUI potentials

The SUI potentials include bioclimatic potentials, exchange potentials, and renewable production potentials. In this development step, the ideal technical potentials known and considered potentially relevant by the energy system developer will be explored. For the next step (concept development) the financial and practical feasibility needs to be taken into consideration as well. In addition, environmental aspects other than energy production potential should be considered, including material requirements. However, to be able to correctly appraise a potential trade-off between energy yield and other inputs (material or financial), the technical potential of energy reduction, exchange and renewable production should be known.

2.6.1. Bioclimatic improvement potential

Bioclimatic potentials aim at a reduction of energy demands through architectural design and renovation measures. Much research can be found on energy-efficient building design, as is already described in the literature review section, and recently also studies on the impact of renovation measures gain more attention, such as, for example, van den Brom et al. (2019).

2.6.2. Exchange potentials

Exchange potentials refer to the exchange of energy between different functions, which can for example occur in the case of simultaneous heating and cooling demands in a neighbourhood. This requires the presence of different functions with different demand profiles within an area, such as swimming pools and offices or a supermarket, as is further described in by the REAP project (Tillie et al., 2010).

2.6.3. Energy potential of local resources

Local renewable energy potentials refer to the potential energy that can be generated in the form of useable energy carriers: electricity, heat or (bio)gas from local ‘primary’ resources: sun, wind, (waste) water, biomass and in some cases geothermal energy. The calculation of energy potentials already involves a selection of potential technologies that convert the primary natural resources into energy carriers. Apart from energy resources, also an inventory of (sub-surface) energy storage potentials, such as aquifer thermal energy storage (ATES), can be included in this step. Energy potential mapping, as described in Section 1.2, is a useful tool for analysing the renewable production potential.

2.7. Step 4: concept development/ generation

The SUI Concept development step involves the design of energy configurations, defined as ‘a combination of energy components, that can efficiently fulfil the required demand by using the available energy potentials’. As each case is characterised by different demands and different potentials, no standardised configurations can be given.

However, the SUI approach provides an overview of the basic available ‘final energy heating options’, presenting different component solutions at the building level, which result in a need for different final energy inputs. These inputs should be provided by the neighbourhood energy configuration, which can be ‘tailor-made’ based on the local energy potentials.

These ‘final energy’ heating options can be separated into *individual* and *collective* options. With individual systems, the heat generation takes place in the building itself; these systems will probably still be connected

to an electricity or gas grid, but they are not connected to a heat grid. Collective systems are connected to a heat grid, which means they can exchange heat between buildings or use collective heat sources and thermal storage facilities.

Individual systems can generate heat from fuels, biomass or by using a heat pump. As fuels and biomass are usually not locally available in urban areas, heat pumps are a more suitable solution. The different options for heat sources for individual heat pumps are shown in Fig. 3.

Collective heat grids can be designed at different temperature levels, as described by Lund et al. (2018). In the SUI project, a categorisation of temperature levels is made based on the question whether the warm (supply) pipe has a sufficiently high temperature to provide direct space heating and/or direct hot water production, or that a (booster) heat pump is necessary. Table 2 shows the different temperature levels of heat grids with related characteristics.

Based on the final energy needs of the alternative described above, different neighbourhood energy configurations can be developed, aiming at a maximal supply with the local energy potentials calculated in step 3.

2.8. Step 5: evaluation and selection

In step 5, the KPI's as described in Section 2.4.2 and Fig. 2 are evaluated. The local renewability fraction, net import of energy, and annual CO₂ emissions of the net energy imported can be calculated using the annual energy balance. For the fraction of autonomy (KPI 2), an energy simulation on a smaller (such as one hour) timestep is needed to assess the simultaneous occurrence of demand and local supply.

3. Case study and application of the SUI approach

3.1. Step 1: case study description & KPI's

3.1.1. Description of the case study Ramplaankwartier (steps 1a and 1b)

The case study involves the Ramplaankwartier, a residential neighbourhood in Haarlem, the Netherlands. This neighbourhood was selected because it has a very active local energy cooperation that was willing to cooperate, as well as close connections with the municipality. In addition, the area is representative for many residential areas in the Netherlands and it contains dwellings from various construction periods.

The total neighbourhood area is 0.35 km², and the Köppen-Geiger climate classification is Cfb, 'temperate oceanic climate'. The average outdoor temperature is 9.3 °C, annual solar irradiation 1107 kW h/m² per year, and precipitation is 794 mm/year (www.knmi.nl). The area consists of 1127 single-family houses and 47 non-residential buildings, according to the public building registration BAG ([Kadaster. Basisregistratie Adressen en Gebouwen \(BAG\)](https://kadaster.nl), 2017), which is a Dutch open

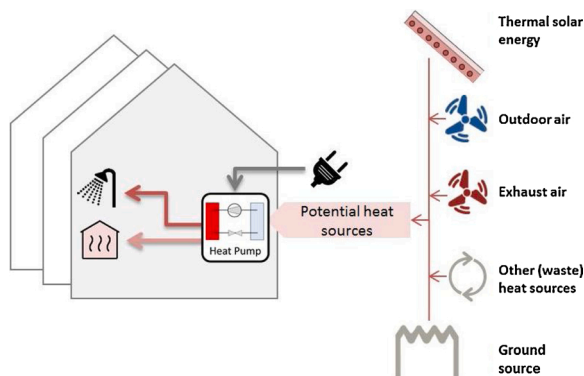


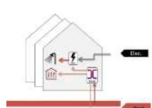



Fig. 3. Individual final energy option for heating: Individual heat pump option with potential heat sources.

Table 2

Final energy options for heating based on a collective heat supply, and categorised according to the temperature levels.

Ultra-low temperature thermal grid		<ul style="list-style-type: none"> - Temperatures: warm ca. 12–20 °C, cold ca 5–12 °C. - Cooling mode: passive cooling. - Heating mode: space heating and hot water must be produced with a heat pump. - This temperature level can be preferred if there is also much cooling demand, and in case the temperature of local sources is below 30 degrees.
Low temperature thermal grid		<ul style="list-style-type: none"> - Temperatures: warm ca. 30–40 °C, return ca 20–25 °C. - Cooling mode: no passive cooling possible, this must be realised with heat pump. - Heating mode: space heating directly; hot water with a heat pump. - This temperature level can be preferred if there is negligible cooling demand, and in case the temperatures of local sources are between 30–40 °C.
Medium temperature thermal grid		<ul style="list-style-type: none"> - Temperatures: warm ca. ca 55 °C, return ca 35 °C - Cooling mode: no passive cooling possible, additional cooling equipment needed. - Heating mode: space heating directly; hot water can be upgraded with an electric boiler. - Preferred if there is negligible cooling demand, if buildings need a higher supply temperature than 40 °C, and in case local heat is available at ca 55 °C
High temperature Thermal grid		<ul style="list-style-type: none"> - Temperatures: warm > 65 °C, return ca 45 °C - Cooling mode: no passive cooling possible, additional cooling equipment needed. - Heating mode: space heating directly; hot water directly. - Preferred mainly in case local heat is available at temperatures > 65 °C, since a lot of distribution losses are introduced at these high temperature levels.

data platform supported by the municipalities. These non-residential functions include a school, a small supermarket, a number of small shops, two childcare centres and a garden centre. Almost all buildings are built between 1920 and 1981, with the majority of the dwellings built between 1920 and 1959. The current energy labels are mainly F and G (see Figs. 4 and 5).

3.1.2. Context (step 1c)

Currently, 93 % of the Dutch dwellings are heated with natural gas supplied (household) boilers (Schoots, Hekkenberg, & Hammingh, 2017). Recently however, the Dutch government has decided to phase out the natural gas supplied systems and therefore, all municipalities need to develop strategies for suitable alternative heating solutions per neighbourhood (EZK, 2018). For this case study, close cooperation with the municipality of Haarlem and with the local energy foundation was established. The local neighbourhood organised the information to and participation of residents, and the municipality is involved in relation to its sustainability goals as well as planning of public works in the area.



Fig. 4. Picture of the area (courtesy of local energy cooperative www.deramplaan.nl).



Fig. 5. Energy labels of the dwellings (map generated by authors based on energielabelatlas.nl).

3.2. Step 2: energy status quo

3.2.1. Existing energy infrastructure & renewable supply (steps 2a and 2c)

In the Ramplaankwartier, there is a natural gas grid as well as an electricity grid to which all buildings are connected. In the current situation, no heat grid is present, and there is no collective energy system such as an ATES (aquifer thermal energy storage). The current renewable energy supply in the neighbourhood consists of several individual rooftop PV panels and one large collective solar roof, together generating 9% of the total current electricity consumption on an annual basis.

3.2.2. Final energy consumption and estimated energy demand (step 2b)

The current final energy consumption is determined using data from 'Energie in beeld' an online platform provided by the grid operators (Enexis, 2018). This platform provided the area's total final electricity and gas use as well as the average use for residential functions per 6-digit postal code. The values for the total case study area are shown in Table 3.

In Table 4, the average gas consumption per household is presented and divided into space heating, hot water, and cooking, based on reference data for hot water and cooking taken from Dutch energy data (BZK, 2016; VEWIN, 2016; VROM, 2009). The gas use for hot water

Table 3

Final gas and electricity consumption for the total case study area.

Final gas consumption [$\text{m}^3/\text{year} \times 1000$]			Final electricity consumption [MWh/year]		
total	residential	non-residential	total	residential	non-residential
2,364	2,041	323	5,279	3,381	1,898

production is adjusted for an average household of 2.5 people, as the average household in the area is larger than the national average of 2.2 persons per household. Based on the average gas use, the net heat demand for space heating and hot water production was estimated using the assumptions for the efficiencies of an average household boiler. These are also shown in Table 4.

In Table 5, the percentage of dwellings per energy label in the area is presented, together with the average gas use per label category according to literature (Majcen, 2016) and the estimated net heat demand. The calculated gas consumption according to these values matches the actual gas consumption for an average floor area of 99 m^2 . For this floor area the gas use per dwelling per label as well as the estimated net heat demand is also presented in Table 5.

3.3. Step 3: SUI potentials

3.3.1. Bioclimatic improvement potential (step 3a)

The potential saving on space heating is determined for the case study area, based on the current energy use, labels, and the estimated net heat demand per label as shown in Table 5. Three renovation levels were considered: 1) Business as usual renovation (BAU, in-between label C and D); 2) renovation for low-temperature heating (approximately label B); 3) Ambitious energy renovation (label A). For the non-residential functions – which represent 14 % of the total gas use - it is assumed that 5% of the gas consumption is used for hot water, and the savings on space heating are considered equal to those calculated for the residential buildings. In Table 6 the resulting heat demand for the total area, for both space heating and hot water, is presented for these different renovation scenarios. Fig. 6 shows the monthly distribution of heat demand per energy renovation solution.

3.3.2. Energy exchange potentials (step 3b)

Since the area is mainly residential, there are no significant opportunities for energy exchange.

3.3.3. SUI renewable potentials (step 3c)

The sources and technologies included in the energy potential inventory are described in Table 7. Also, several potentials to regenerate seasonal low-temperature heat storage, such as ATEs, are included. These are energy 'sources' at near-environmental temperatures, also sometimes called 'environmental energy sources'. As explained in Section 2.6, the technical potential is explored, while financial and other evaluations can be included later. This way various technically feasible sources are included in the search for diverse and innovative configurations.

The resulting energy demands (from Table 6) and the potentials are shown in Fig. 7. In this figure, the colour of the bars of the heat potentials represent the temperature of the available heat: dark red represents a temperature around 60°C , and the light blue at the other end represents 10°C .

As can be seen, there are many low-temperature heat sources available. When comparing these to the heat demands at the left side of the figure, it can be concluded that in principle, all heat demands can be supplied with low-temperature heat sources available. However, these are not yet at the right temperature level, which means upgrading is needed. Various solutions for this will be developed in step 4 of the SUI approach.

In Fig. 8 the energy potentials are shown on a monthly basis,

¹ The actual average dwelling size in the area is 5% larger. This can have several reasons: it can mean that the dwellings on average use slightly less energy than the national average, or the labels are slightly better in reality than registered, or the largest dwellings have the best energy label. Since these details are not known, for further analyses an average dwelling size of 99 m^2 is considered

Table 4

Final gas consumption and estimated heat demands for an average household (hh) in the Ramplaankwartier.

Estimated average final gas use per residential function				Assumed boiler efficiency		Estimated heat demand	
m ³ /household per year				% of LHV		(kWh/household/year)	
total	cooking	hot water production	space heating	for hot water (*)	for space heating	for hot water	for space heating
1,811	66	420	1,325	61 %	85 %	2,490	10,952

(*) The boiler efficiency for hot water includes the stand-by losses of the boiler tank (average 500 kW h per household per year).

Table 5

Division of dwellings in the area according to their label & final gas consumption per label according to average values from literature (Majcen, 2016).

label	Label A	label B	label C	label D	label E	label F	label G
% present in Ramplaankwartier	1 %	2 %	15 %	12 %	16 %	26 %	28 %
Final gas consumption according to in m ³ /m ² per year	11	13	14.5	16.5	18.5	19.5	20.5
Final gas consumption for an average dwelling of 99 m ²	1,089	1,287	1,436	1,634	1,832	1,931	2,030
Estimated annual gas used for space heating (m ³ /dwelling)	603	801	950	1,148	1,346	1,445	1,544
Estimated average heat demand for space heating (kWh/hh per year)	4,986	6,622	7,849	9,486	11,122	11,940	12,758

Table 6

Estimated heat demand per energy renovation solution.

Renovation	Explanation	Space heating (MWh/yr)		Hot water (MWh/yr)	
		Residential	Non-resid.	Residential	Non-resid.
Status quo (no renovation)	No renovation	12,364	2,536	2,806	96
Business as usual renovation	All labels E,F,G to label C/D	9,673	1,984	2,806	96
renovation to label B	All labels C,DE, F,G to label B	7,441	1,526	2,806	96
renovation to label A	All labels B,C, DE,F,G to label A	5,619	1,152	2,806	96

presenting potential electricity supply in the upper graph and thermal supply in the lower graph. Comparing Figs. 6 and 8 clearly demonstrates that there is a mismatch in time between the available energy and the energy need, which means substantial, seasonal energy storage is needed if we want to make use of the available local resources.

3.4. Step 4: concept development

3.4.1. Case study: energy configuration options

For the case study, four energy options have been developed, using the basic 'final energy options' of Fig. 3 and Table 7 and the available renewable supply potentials shown in Fig. 7. These four energy options are described in Table 8. The use of wind energy can be added to all systems, and therefore it is not included in the schemes. In addition, the wind potential is making use of area's outside of the built area, and are

therefore in practice not easy to realise.

3.4.2. Combining energy configuration options with renovation scenarios

The four energy configurations are combined with building renovation scenarios suitable for the related configuration. The suitability depends on the temperature required by the emission systems (e.g., radiators) for a given renovation, and the temperature achievable by the energy configuration. The suitable combinations are listed in Table 9, including the heat pump performance of each combination. As described in Section 3.3.1, the deep renovation scenarios are difficult to realise in many of the dwellings. This will have to be taken into account in the final evaluation.

Table 10 presents the energy balance of all combinations: it shows the net heat demand of all buildings in the area, for each option, the heat losses in the system, and the resulting required electricity input. Also, the required heat as a source for the heat pumps is shown.

3.5. Step 5: assessment and evaluation

3.5.1. Local renewability, fraction of autonomy and net electricity input

Table 11 shows, for all combinations, the first three key performance indicators: Local renewability fraction, fraction of autonomy, and net electricity input. Since the aim for the configurations to be developed was maximised local energy balance and thereby minimised energy input need from outside the area, these KPI's are selected in step 1.

For the fraction of autonomy, hourly data have been used. For this analysis the use of wind energy is not included, since both options (a large-scale wind turbine as well as more local and smaller turbines) are actually not available within the built area, but only on the surrounding (farmer) lands. However, the complementary profile of wind as shown in Fig. 8 could greatly improve the fraction of autonomy of all cases.

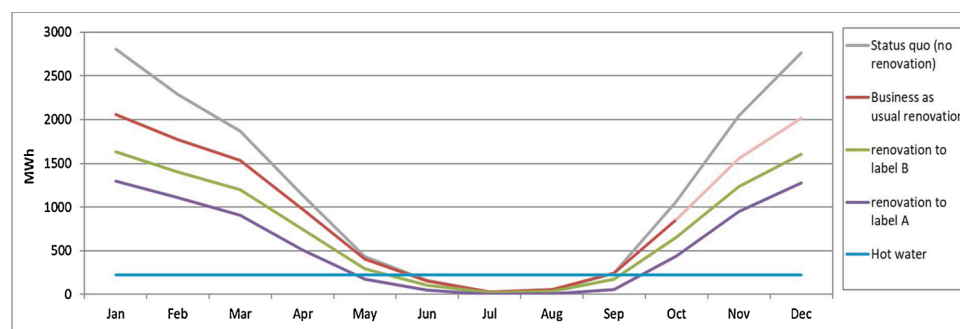
**Fig. 6.** Monthly heat demand profile per energy renovation solution.

Table 7
Energy potentials considered in the case study.

Source	Technology	Method and references
Solar energy in the area		The solar energy potential was based on roof-mounted panels, where an average of 12 panels per building was assumed.
	PV	The potential yield of PV-panel is based on the annual average solar radiation on the tilted panels (1107 kW h/m ² per year for Haarlem), the surface area of the mounted panels on the roof (in m ²) an efficiency of the solar panel of 16 % and a performance ratio of 85 %.
	PVT	Uncovered collectors with water as the heat transfer fluid were assumed. The electrical and thermal yield potentials for all buildings have been estimated for LT (low temperature) and HT (high temperature), using (Helden van, Roossien, & Mimpfen, 2013) and validated with the simulation software PolySUN for the case study location.
	PT	The yield of covered solar collectors was based on (Helden van et al., 2013;) for both the LT and HT output. The results are validated with the simulation software PolySUN for the case study location.
Wind	Urban wind	For this study, the potential yield of an XZERES Skystream 3.7 TM wind turbine is calculated with the software Homer Pro, based on application on 70,000 m ² of the surrounding green areas.
	3 MW turbine	The electricity output of a 3 MW windmill is added as a reference, even though this technology cannot be implemented in the case study area due to legal and other constraints.
Wastewater	Wastewater	The thermal energy that can be extracted from the sewer pipes is based on an available flow of 6.5 L/s, and a delta T of 2.5 K is, which is considered feasible using current sewage heat exchangers.
		The sources below only generate heat between approximately April and September and can, therefore, only be used as regeneration for seasonal low-temperature heat storage, such as ATEs systems. The values are based on a study commissioned by the City of Haarlem (De Brauw, Koezjakov, & Meddeleer, 2018).
ATES regeneration potentials	Asphalt collectors	An asphalt collector is a type of solar collector that generates heat via a pipe system installed under the road surface. An annual yield of 1 GJ/m ² is considered feasible, and for the total yield, 3 km of a nearby 4-line provincial highway is assumed.
	Dry coolers	It is assumed that dry coolers extract heat from the outside air when the outside temperature is 10 °C or higher, which occurs at least 4,000 h per year in the local climate. The annual potential is determined for 1 dry cooler with 4 fans, measuring approximately 15 m by 2 m, with a height of 1.5 m.
	Surface water	The thermal energy from surface water is based on the only flowing water nearby (Brouwersvaart), which has a capacity of 50 m ³ /hour. Furthermore, a delta T of 6 K and 4,000 h per year of sufficiently high temperatures is assumed.

3.5.2. CO₂ emissions

For calculating the CO₂ emissions, three different emission factors have been applied in order to evaluate the sensitivity for the emission factor, see Table 12.

For this evaluation, the total CO₂ related to both heating and user electricity presented, and the avoided CO₂ due to on-site electricity

production on the building is subtracted. Also the status quo situation with gas fired boilers is included for the comparison. For a fair comparison, the same amount of solar PV panels is assumed for the status quo as for the renovated buildings; otherwise a reduction of CO₂ could just be the result of placing PV panels. The resulting total CO₂ emissions in ktons per year for the entire area are shown in Fig. 9.

As could be expected, the effect of the CO₂ emission factor is similar for all alternative options developed, since all these alternatives use electricity as the only external energy input. Even more extreme: when all electricity produced will be CO₂ emission free, all systems will perform equal in terms of CO₂. Still, their performance on local renewability differs, which means one system requires more externally produced electricity than another, which in term means a larger or smaller amount of renewable electricity needs to be produced somewhere.

But before we reach the point that all electricity production is CO₂ emission free, the comparison with the status quo - which is based on natural gas - differs significantly for each emission factor. A high emission factor results in only little CO₂ reduction of option 4 (the high-temperature heat grid without building renovation) compared to the gas scenario; the other alternatives still present a significant CO₂ emission reduction. For all electricity-based options, the reduction in CO₂ emission compared to the gas option is obviously larger for lower CO₂ emission factors. This graph shows that it is essential to select the right CO₂ emission factor in order to correctly predict emission reductions. Furthermore, the seasonal imbalance and its effect on the actual CO₂ emission factor could also be considered; in this case avoided electricity import (due to electricity export) is accounted for with the same emission factor as imported electricity.

3.5.3. Selected option for further development

Based on the energy KPIs, the best options are 2c and 2d (ULT heat grids with label B and A renovation) and 3c and 3d (LT/MT heat grid with label B and A renovation). Obviously, the higher the insulation level after energy renovation, the lower the energy demand and - given the same supply system - the higher the fraction of local supply and autonomy. This means that energetically the most preferred option would be 3d, - also matching the smart urban isle aim of a 'smart local energy system that minimizes the need for external energy'.

However, for the practical viability of the project some feasibility aspects were also considered, resulting in the aim to maximize energy performance while still being financially and practically feasible. This means financial and practical issues were considered boundary conditions and not optimization objectives. While a detailed financial analysis was not performed within this study, the experience of residents described in Section 3.3.1, showed that deep retrofitting is both technically and financially challenging for many buildings. The energy improvement of insulation level d compared to c of around 16 %, would probably not justify the investments and 'hassle' of performing deep renovation. However, the dwellings that will be insulated to a higher level can still be part of the neighbourhood energy system as well. In that sense, the choice between insulation level c and d is not a 'one or the other' selection; in the next phase further analysis per dwelling type can show the best insulation level.

The more essential choice is between options 2 (ULT) and option 3 (LT/MT). Option 3 (LT/MT heat grid with large collective heat pumps) requires slightly less electricity than option 2 (ULT heat grid). However, for this specific case study area option 3 has some essential disadvantages compared to option 2. Firstly, the most important drawback of option 3 (LT/MT grid) is that less heat from the PVT collectors can be generated because a higher temperature is needed for the thermal grid, resulting in the need for more PVT surface which is difficult to realise on the existing buildings. A second drawback of the LT/MT grid is that three or four large collective heat pumps are needed in the area, requiring considerable space and related visual impact.

Hence, for this specific case study with many existing dwellings, option 2 is more promising. An LT/MT grid (option 3) could have an

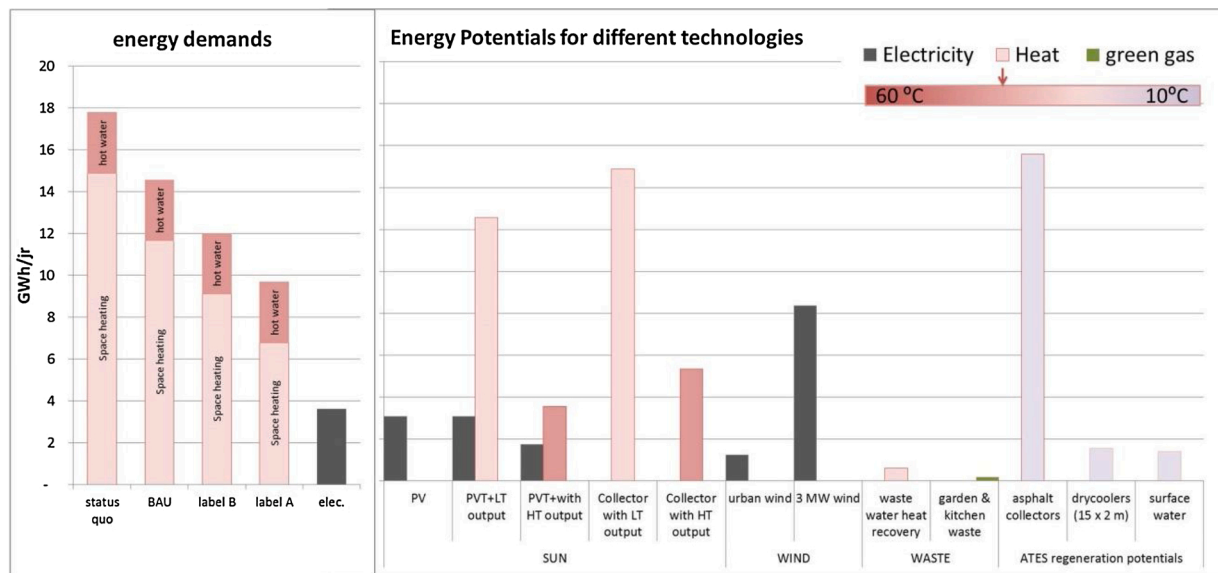


Fig. 7. Local energy potentials for different technologies, divided into: potential electricity production (in grey), potential thermal production (the colour varies according to the temperature of the output, light blue for 10 °C and dark red for 60 °C), and potential green gas production (green).

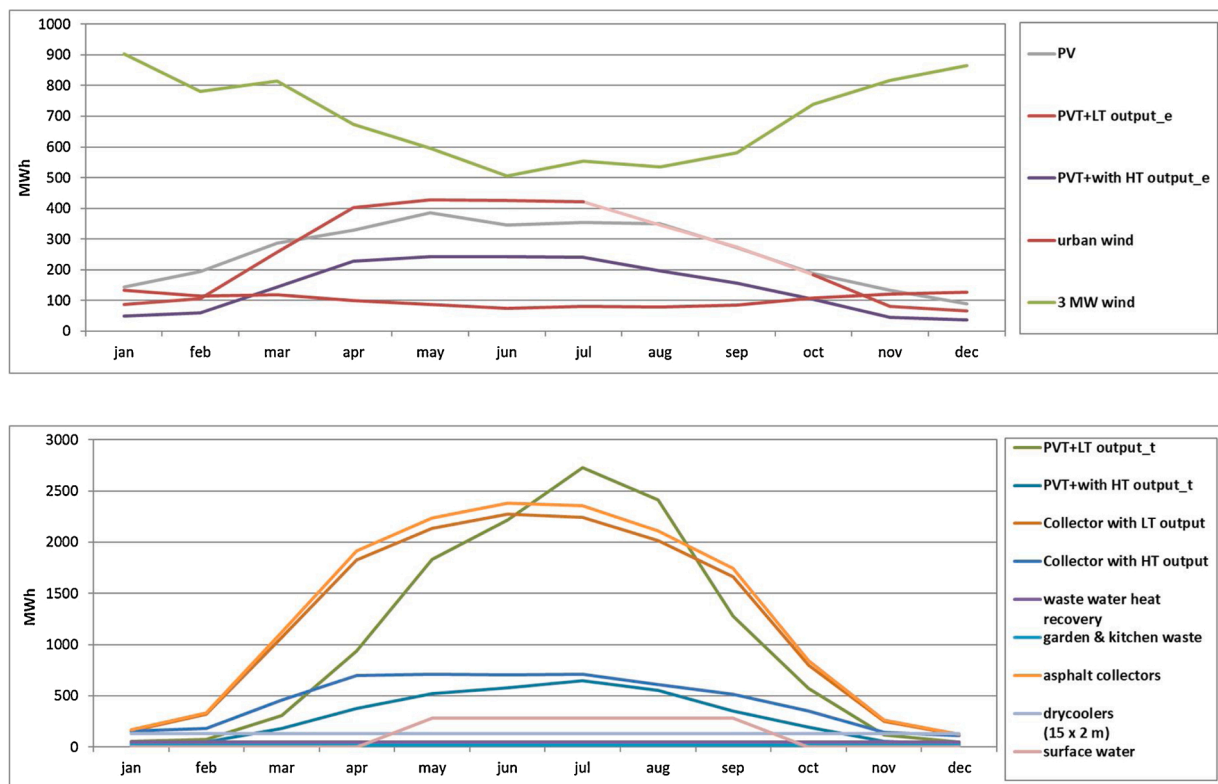


Fig. 8. Monthly local energy potentials profiles (electricity potentials - top) and (thermal potentials - bottom).

advantage over an ULT grid (option 2) if there would be significant heat sources in the neighbourhood at a temperature above 40 °C, which can directly feed into the LT/MT heat grid. Also, if all the dwellings would have a very low-temperature emission system, i.e. below 40 °C, option 3 could become more advantageous. In the case study presented this is not feasible due to the properties of the existing dwellings, but in new developments low-temperature emission systems are very common and then option 3 can reduce the installed peak power of all the heat pumps by collectively producing the heat for space heating.

Evaluating the advantages of each system, the ULT grid (option 2) is


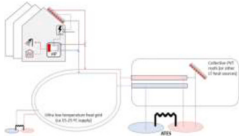
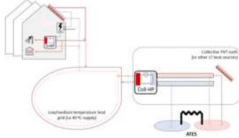
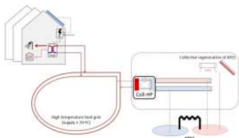
selected for further development. The concept is currently being further developed with technology developers and local stakeholders and referred to as 'decentralised solar heat grid'.

4. Discussion and recommendations

This research aimed at developing a novel approach for generating various concepts for sustainable neighbourhood energy systems and demonstrating its usefulness in application to a case study. The approach has shown to be useful, but several aspects can be added or improved to

Table 8

Energy configurations developed for the case study, matching the demand with the available sources.

Option 1) Individual air source heat pump		<p>Each building has an individual heat pump using the outdoor air as a heat source. As not all dwellings are suitable for individual ground source or solar thermal heat pumps, the air source heat pump option is selected for the comparison.</p> <p>The ULT heat grid is connected to Aquifer thermal storage (ATES). In winter, the heat grid functions as a source of the heat pump; in spring and autumn, the thermal output of PVT is used by the heat pump; in summer, the overproduction of the PVT is used to regenerate the ATES, which would otherwise not in annual thermal balance.</p> <p>The LT/MT heat grid is connected to an provided by a collective heat pump which is connected to an ATES. Space heating is directly supplied by the grid; hot water is produced with a booster heat pump. As in option 2, individual PVT can be used to regenerate the ATES system, but as the output of PVT is lower for higher temperatures (see Fig. 7), more collective regeneration must be accounted for in option 3 than in option 2.</p> <p>A collective HT heat pump is used to feed a HT heat grid, which is directly able to supply both space heating and domestic hot water.</p> <p>This option uses PV on the dwellings instead of PVT, since the low-temperature output of the PVT cannot be utilized in this concept. This means the generation of the ATES needs to be provided with other sources near the ATES wells. In this case, drycoolers are considered.</p>
Option 2) Ultra-low temperature (ULT) heat grid with individual heat pumps and PVT		
Option 3) Low/medium temperature heat grid with booster heat pumps at the dwelling level.		
Option 4) High Temperature (HT) heat grid with a collective HT heat pump		

enhance the approach. These are mainly: including societal, legal and practical aspects; providing as realistic input parameters and assumptions as possible; adding performance indicators; and clarifying the boundary conditions of the system. These are briefly explained in the following sub-sections.

4.1. Societal, legal and practical aspects

This research was conducted in close cooperation with the local energy cooperation and many residents. Therefore, the practical aspects in relation to building renovation solutions was implicitly included in the development and evaluation of the energy concepts. However, a more explicit relation with other societal aspects and legal constraints can be included in a further development of the approach. Step one would be to include legal and practical constraints explicitly in the evaluation, although the technical potential should always be the start; then it can be decided whether it is worth it to (try to) overcome some practical or legal barriers.

Going one step further than just considering societal, practical and legal constraints, a more integrated process could also be further developed. The two papers on energy planning and stakeholder engagement reviewed in Section 1.2.2 (Neves et al., 2015 and Hettinga et al., 2018), already mention the phase of generating alternative solutions; the SUI approach could be embedded in these broader processes.

4.2. Further research on input parameters and assumptions

In the application of the approach, several assumptions have been made regarding the efficiency of equipment or the functioning of the system. The following assumptions have great influence on the results and should be investigated in more detail: 1) The required temperature needed by the emission systems in relation to the level of insulation and renovation in different building types. This is an important factor determining the suitability and performance of a heat pump and the system as a whole; 2) The actual performance of several energy components such as heat pump performance, especially in unconventional situations such as low temperature solar heat grids; 3) The distribution heat losses of the grid in relation to grid insulation levels, as well as the pumping energy for the different options. 4) In addition to these technical assumptions, also the realistic cost estimation is very important. For this paper only clearly non-feasible solutions were not further studied, but for the next phase of detailed system design and selection of (insulation) materials and components, the costs of all measures should be estimated with more detail.

4.3. Additional performance indicators

In this paper, the focus has been on energy neutrality, local energy balance and local self-sufficiency. For a more holistic assessment, additional indicators should be added. Firstly, it is recommended to add indicators on energy performance in relation to the overall energy grid challenges, such as peak power demand (which determines the capacity of the grid) and energy flexibility (ability to provide flexibility to the national electricity grid). This is also in line with the indicators provided by Ala-Juusela et al. (2016). Secondly, with the aim to achieve a circular society by 2050, the total environmental performance and circularity of the materials should be included. The first step is to look at the Energy Return On Investment (EROI) of the materials needed for the energy system (Capellán-pérez, De Castro, Javier, & González, 2019). To achieve circularity is even more complex, since it involves not only the energy used for the materials but the design of the entire energy system to be fully circular: all materials are either rapidly renewable materials, or designed for total reuse (Heisel & Rau-oberhuber, 2020). This challenge is even larger than achieving local energy balance for the operational energy, which was the focus of this paper, and it still requires extensive research. A third, more practical aspect of the evaluation is related to the spatial requirements of the systems under consideration, such as the required roof or land surface necessary for renewable energy production, as well as the spatial requirement for all technical equipment within the dwellings. In the study this aspects was implicitly included, but it is relatively difficult to quantify. A first attempt to quantify spatial requirements as well as the related visual impact has

Table 9

Combinations of energy system configuration and renovation scenario considered for evaluation.

SUI mini-network configurations			Space heating demand for various scenarios				Hot water
			Status quo	Renovation Scenarios			All scenarios
			a	b 'BAU'	c 'Label B'	d 'Label A'	
Estimated required temperature of the heat emission system: (°C supply/return)			75/65	60/45	50/40	40/30	
# Configuration	Grid/source temperature		(COP space heating of the individual heat pump for space heating between brackets)				(COP for hot water)
1 Individual heat pump	2 °C				1c (3.1)	1d (3.7)	(2.2)
2 ULT grid with individual HP	15 °C			2b (3.9)	2c (4.3)	2d (5.7)	(3.2)
3 LT/MT grid with individual booster HP	20–40 °C			3b (5.5)	3c (6.5)	3d (n.a.)	(4.2)
4 HT grid with collective HT heat pump	70 °C		4a (n.a.)	4b (n.a.)			

Notes:

- The COPs mentioned are the COPs of the individual heat pumps based on the performance of 50 % of Carnot and the given temperatures, with an additional delta T between condenser and evaporator of 5 K, to account for the internal versus external delta T of the heat pump. This is a theoretical approach, as can be found in (Meggers, Ritter, Gof, Baetschmann, & Leibundgut, 2012).
- For domestic hot water preparation, an additional correction for option 1 is included, assuming 10 % of the hot water is produced with auxiliary energy when outdoor temperatures may be too low.
- For the collective heat pump of options 3 and 4, a COP of 60 % of Carnot is assumed, resulting in a COP of 7.3 for option 3 and a COP of 3.3 for option 4.

Table 10

Energy balance of all heating scenarios.

renovation scenario	Option 1 (individual HP)		Option 2 (ULT heat grid with individual HP)			Option 3 (LT/MT heat grid with booster HP)			Option 4 (HT heat grid)	
	c	d	b	c	d	b	c	d	Status quo	b
	label B	label A	(BAU)	label B	label A	(BAU)	label B	label A	(a)	(BAU)
Net heat demand of buildings (GWh/yr)	11.9	9.7	14.6	11.9	9.7	14.6	11.9	9.7	17.8	14.6
Building level boiler losses (GWh/yr)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6		
Neighbourhood grid distribution losses (GWh/yr)						0.6	0.6	0.6	2.8	2.8
Total electricity needed for heating (GWh/yr)	4.5	3.4	4.1	3.2	2.3	3.5	2.8	2.1	6.5	5.5
Net electricity import needed for heating systems (GWh/yr)	1.4	0.4	1.0	0.1	−0.8	0.5	−0.3	−1.0	3.4	2.4
Net electricity input when including user electricity of 2.2 GW h/yr (GWh/yr)	6.7	5.6	6.3	5.4	4.5	5.7	5.0	4.3	8.7	7.7
Electricity production										
Local electricity production from PVT (GWh/yr)	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Heat sources & ATEs regeneration (GWh/yr)										
Air as a source for HP or ATEs regeneration with dry-coolers	7.9	6.8							14.1	11.9
Thermal output from PVT used as a source for the heat pumps.			11.0	9.3	8.0	12.2	10.3	8.7		

Table 11

KPI's of all heating scenarios.

renovation scenario	Option 1 (individual HP)		Option 2 (ULT heat grid with individual HP)			Option 3 (LT/MT heat grid with booster HP)			Option 4 (HT heat grid)	
	c	d	b	c	d	b	c	d	Status quo	b
	label B	label A	(BAU)	label B	label A	(BAU)	label B	label A	(a)	(BAU)
Local renewability fraction (%) Electricity (*)	31 %	35 %	33 %	36 %	41 %	35 %	38 %	42 %	26 %	29 %
Fraction of autonomy (%) Electricity (*)	13 %	15 %	13 %	14 %	15 %	14 %	16 %	17 %	12 %	13 %
Net electricity input when including user electricity (GWh/yr)	6.7	5.6	6.3	5.4	4.5	5.7	5.0	4.3	8.7	7.7

(*)The renewability fraction and fraction of autonomy are only considered for the electricity: the locally produced electricity / the total electricity need, for both the heat pumps and the user related electricity. As the locally produced heat is all locally stored and reused, and no heat input from outside the area is considered, the fraction of autonomy and local renewability of the heat used, on the area level, is both 100 %.

been made in (van Amstel, 2018) and this approach could be embedded in the evaluation. Last but not least a cost indicator should be included. Both cost and practical implementation aspects determine the optimum between building and neighbourhood measures. For this study, a quick scan of financial feasibility of building renovations is performed, but more complete and accurate cost estimations will be needed and a total cost of ownership approach should be applied.

4.4. Boundary conditions and externally available resources

On a regional and national scale, more research is needed on the boundary conditions for sustainable neighbourhood energy systems. As is shown in Section 3.5.2, the CO₂ emission factor greatly influences the results, mainly affecting the comparison of electricity based alternatives with heating systems based on other carriers than electricity. As the CO₂ emission factor is a result of both (increased) renewable production and (increased) electricity demand, more research is needed on the most

Table 12
CO₂ emission factors used.

Energy carrier	type	Value	Unit	Source and additional information
Natural gas		1.890	kg/m ³	www.co2emissiefactoren.nl – emissionfactors 2018
Electricity	Grey electricity	0.649	kg/kWh	www.co2emissiefactoren.nl – emissionfactors 2018
	Dutch electricity mix	0.413	kg/kWh	www.co2emissiefactoren.nl – emissionfactors 2018
	Expected mix in 2020	0.340	kg/kWh	NTA 8800 ‘Energy Performance of Buildings – Determination Method’ (Lund et al., 2018)

appropriate CO₂ emission factors, taking this relation into account. This is needed to implement the most cost-effective CO₂ reduction solutions and avoid investing in solutions that lead to negligible emission reductions.

Furthermore, the comparison with other forms of energy input from outside the area than electricity is currently challenging. For example: if, instead of electricity import, an option would have been developed that imports biomass or high temperature heat, the comparison of alternatives becomes quite unclear, as there is no basis for a comparison other than CO₂. The availability and the environmental impact of the entire supply chain of other energy sources, such as biomass or green gas, must be considered to enable a comparison between local and external energy resources and between different external resources. Potentially, an exergy efficiency indicator could play a role here as an indicator showing to what extent the resources are being optimally used (Bejan et al., 1996; Jansen, Fremouw et al., 2018; Jansen, 2013).

5. Conclusion

This paper presented a new approach for generating various concepts for local energy systems that maximize the use of local renewable resources. This approach was developed as part of the European ‘Smart Urban Isle (SUI)’ project. As shown in this paper, this approach can be

used to generate alternative solutions for neighbourhood energy systems, with maximised local energy balance. As became clear from the discussion and recommendations section, the overall challenge to achieve sustainable cities is much more complex and many other aspects need to be considered. However, the SUI approach already adds to the available methods for designing urban energy systems. Three conclusions on the approach can be drawn:

5.1. Conclusion 1: the approach can lead to the development of an innovative local energy system

The approach provides a systematic structure, while at the same time leaving room for the development of new and innovative configurations based on the local energy demand and local energy potentials. In the case study example, the approach led to an innovative local energy system concept with a high share of local renewable energy supply.

5.2. Conclusion 2: a promising novel neighbourhood energy concept was developed, which is also applicable to other, similar neighbourhoods

The innovative concept developed for the case study involves a so-called ‘decentralised solar feed-in heat grid’, which is a novel application of individual PVT panels and heat pumps in combination with an ultra-low temperature thermal grid. Depending on the season, the heat needed for the heat pump is provided by either the grid or the PVT panels. The summer heat surplus produced by the PVT panels is exported to the grid in order to be stored in the ATES system. This results in very high performance of the heat pump and thereby very small electricity needs. In fact, the electricity from the same panels suffices for the heating system.

The concept was developed for the case study, an existing residential neighbourhood in a moderately cold climate (the Netherlands), which means the heat demand is dominating, and cooling demand is significantly lower. In this particular case study, there are no significant (waste) heat sources available, and, due to the dominating heat demand, a subsurface seasonal storage system (ATES) would be in unbalance without regeneration.

Since the concept only uses locally generated heat and electricity, it

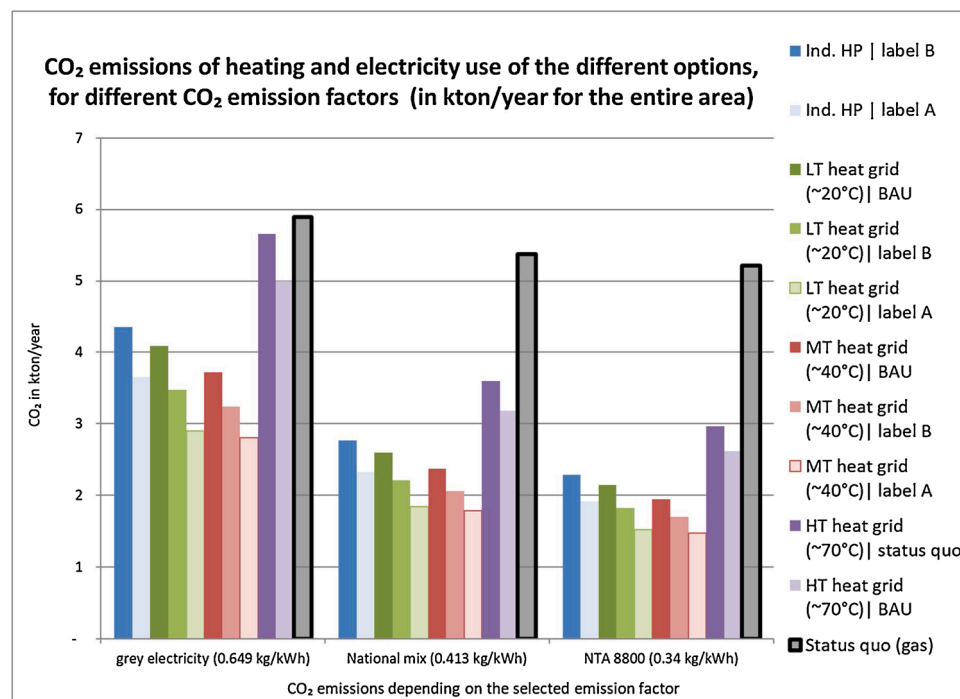


Fig. 9. CO₂ emissions of the different heating solutions.

is thereby applicable to similar residential neighbourhoods, with a dominating heat demand and negligible heat sources other than the sun.

5.3. Conclusion 3: the neighbourhood scale has great potential to optimize energy flows

As stated in the introduction and by previous authors, the neighbourhood scale has great potential to increase energy performance and thereby sustainability, compared to solutions at building level only. This statement was confirmed by the results of this paper, by showing that a better energy performance could be achieved with a neighbourhood solution than with an individual solution, given the same building insulation levels. These findings add to the knowledge that especially for existing buildings a neighbourhood approach can be beneficial, since thorough energy demand reduction may be technically or financially difficult. By selecting a the level of energy reduction in combination with a neighbourhood system that fits this energy demand, an overall highly efficient solution can be developed. In addition, it was shown that, for an energy efficient solution, it is important to not only look at energy reduction potential in terms of GJs or kWhs per year but also at the temperature levels required by the building energy system, as this greatly determines the possibilities and efficiencies of the local energy system.

Declaration of Competing Interest

The authors report no declarations of interest.

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