The role of seasonal thermal energy storage in increasing renewable heating shares: A techno-economic analysis for a typical residential district

McKenna, Russell; Fehrenbach, D.; Merkel, E.

Published in:
Energy and Buildings

Link to article, DOI:
[10.1016/j.enbuild.2019.01.044](https://doi.org/10.1016/j.enbuild.2019.01.044)

Publication date:
2019

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
McKenna, R., Fehrenbach, D., & Merkel, E. (2019). The role of seasonal thermal energy storage in increasing renewable heating shares: A techno-economic analysis for a typical residential district. *Energy and Buildings*, 187, 38-49. <https://doi.org/10.1016/j.enbuild.2019.01.044>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

The role of seasonal thermal energy storage in increasing renewable heating shares: a techno-economic analysis for a typical residential district

McKenna, R.^a, Fehrenbach, D.^b, Merkel, E.^c

^a Systems Analysis, DTU Management Engineering, Technical University of Denmark (DTU), Kongens Lyngby, Denmark, rkenna@dtu.dk

^b European Institute for Energy Research (EIFER), Karlsruhe, Germany, fehrenbach@eifer.org

^c Chair for Energy Economics, Institute for Industrial Production (IIP), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, erik.merkel@partner.kit.edu

Abstract

European renewable energy developments have so far focussed on electricity generation, with relatively modest progress in renewable heating. Partly this is due to the temporal mismatch between solar irradiation availability and residential heating demand profiles. Seasonal thermal energy storage (STES) has been proven in several pilot projects and is market ready, albeit not currently economical. This paper sets out to assess the potential contribution of STES to increasing the renewable heating fraction in residential buildings. An existing mixed integer linear program (MILP) is extended to consider STES and applied to optimize the energy supply system for a typical residential district with efficient new-build apartment buildings, in the context of five contrasting scenarios. Achieving 100% renewable heat supply requires significant capacities of seasonal storages and is associated with substantially (14%) higher cost than in the reference scenario. To achieve a 60% renewable heat supply fraction under today's framework conditions, the cost increase compared to the reference scenario is only marginal (1%). The results in three future scenarios reflecting possible conditions in 2030 demonstrate that even higher levels of renewable heat supply could soon become economical. Overall the recommendation is to aim for renewable heat supply levels of around 60-80% combined with demand side measures such as improved insulation. Further work should focus on more systematically exploring the relationship between the grid renewable electricity fraction, available solar collector area and the optimal renewable heat integration strategy.

Keywords

Renewable heat; seasonal thermal energy storage; residential buildings; mixed integer linear programming

1. Introduction

The transition to renewable energy is well underway in many countries, with primary renewable energy production in the EU increasing by 66% between 2006 and 2016 (Eurostat 2018). However, the development so far has focussed on electricity (currently around 30% renewable), with less than 20% of heat supply in Europe from renewable sources (ibid.). This is despite the fact that space heating of buildings account for around 40% and 36% of European final energy demand and greenhouse gas emissions respectively (De Groote and Rapf 2015).

Especially renewable heat derived from solar irradiation, i.e. through solar thermal (ST) and/or photovoltaics (PV) with heat pumps, is clearly very variable. Hence, integrating renewable heat into the energy system requires both short and long term storage systems. Short term storage systems can account for short term stochastic fluctuations in the supply, for example due to changing local weather conditions. Long term storage, on the other hand, is aimed at overcoming the largely

deterministic challenge, that solar irradiation is highest in the summer, whereas space heating demand peaks in the winter months.

Seasonal thermal energy storage (STES) systems are at an advanced stage of development and have been piloted in several countries¹. As shown in section 2, many of these pilot projects are in Germany, where the technology is considered to be market-ready and promises to benefit from future cost reductions due to upscaling and learning curves (Solites 2012). Hence, these storage technologies could conceivably become economically competitive within the coming years, thus playing a central role in the renewable heating transition (IEA 2015).

The literature review in section 2 also highlights that, whilst several studies have analyzed STES in some technical detail, most are based on simulating approaches. The technological focus has also mostly been on solar thermal, and the sizing of the STES has not been of particular interest. Two studies perform a pure optimization approach (Gabrielli et al. 2018 and Welsch et al. 2018), but neither analyzes the integration of STES at the neighbourhood level or considers the competition and synergy effects with other technologies. Finally, existing optimizations have focused on technical aspects, whereas the present contribution is also geared towards economic criteria, thus complementing the technical focus.

To the authors' knowledge, no study has yet analyzed the possible contribution of STES to the integration of renewable heat in the residential sector in the context of a wider energy system analysis of a typical residential district. Doing this therefore forms the general objective of this study, which thereby poses the following research questions:

- What size of storage is needed for a typical residential district to integrate large amounts of renewable heat?
- How sensitive are results to assumptions, e.g. what are the interaction effects with other technologies such as heat pumps? What impact do the grid renewable energy fraction and available collector surface have on the optimal system configuration?
- What prospects do these technologies have to contribute to the integration of heat in the near future?

In particular, the focus here is on the relationship between the grid renewable energy fraction and the size of the seasonal storage required, under different framework conditions. The method employed consists of a mixed integer linear programming (MILP) approach, with detailed techno-economic depiction of competing heating technologies at an hourly resolution. The so-called POPART model (cf. section 3) is employed in the context of a case study to analyze the cost-minimal energy supply system for a typical residential district, under varying constraints relating to the required renewable heat fraction and the CO₂ emissions intensity of the electricity imported from the network.

The remainder of the paper is structured as follows. Section 2 presents some background to STES and reviews the literature for studies relating to this topic. Section 3 then presents the methodology based on the POPART model and important assumptions made in the present case. Section 4 further includes the results and discussion, before the paper closes with a summary, conclusions and an outlook in section 5.

2. Seasonal thermal energy storage: background and literature

a. Development status of seasonal thermal energy storage

Seasonal thermal energy storage has already been researched for several decades. The first demonstration plants were realised in Sweden in the late 1970s (Solites 2012) and in Germany in the 1980s. These early systems were combined with district heating systems, in order to increase the overall heat utilization by shifting heat from the summer into the winter.

Broadly speaking, there have been three generations of STES. The first generation systems in the 1990s were proof of concept and focused on simplicity. At the beginning of this century, the second generation systems were more focussed on different technological storage alternatives, system integration of the heat supply (e.g. using high performance concrete in Hannover). The third generation systems post 2005, including many different industrial actors, have been focussed on increasing overall efficiency and reliability, integrating heat pumps and multi-function heat supply. The systems have now reached a stage of market-readiness, where no further basic research is required, instead only primary technology transfer (Solites 2012). From 2nd to 3rd generation a cost reduction of about 30% has been achieved and the target for market entry is in 2020, with diffusion and further cost reductions (an additional 20%) by 2030 (IEA 2015).

Several large-scale International research projects have and/or still are further developing STES technologies¹. Despite these activities on the international scale, Germany is one of the world leaders in this field. Two large research programmes, Solarthermie-2000 and Solarthermie-2000plus, have led to several pilot projects being funded and realised. Since 1996, 11 research and demonstration plants have been built (cf. Figure 1). Typically, these systems aim at a solar fraction of 50% or higher (measured as the fraction of total annual heat demand that is met by the solar thermal plants) – mostly reached in these projects.

Several system configurations are available for STES. Although these systems differ in their characteristics, the employed principle of storing sensible thermal energy for longer periods of time, is the same (Table 1). Tank Thermal Energy Storage (TTES) systems are large, well-insulated metal and concrete tanks, constructed underground and filled with water. Their wall construction is complex due to the requirements to protect from moisture penetration from the outside as well as to enable evaporation if the insulation is wet. Pit Thermal Energy Storage (PTES) systems are similar, but instead use an evacuated pit as their base and walls. They may be filled with a water/gravel mixture and have a fixed or floating lid. Hence, for the same storage volume a PTES takes up more space, but due to its higher solidity it can be employed as a foundation, for example for underground parking facilities. Two other alternatives, namely Borehole (BTES) and Aquifer (ATES) systems, have much lower energy storage densities (heat capacities) and are therefore not further discussed here.

Table 1: Characteristics of Seasonal Thermal Energy Storage Technologies (sources: IEA 2015, Solites 2012, Schmuck 2017)

	Typical heat capacity (kWh/m ³)	Efficiency (%)	Storage medium	Investment (€)	Investment (€/m ³)
TTES	60-80	50-90	Water	185668	103
PTES	30-50	50-90	Water/gravel	121790	30
BTES	15-30	50-90	Water	Varies	Varies

¹ International activities focussing on seasonal thermal storage systems include the PIMES research project (www.pimes.eu), which analyzes this technology for three European locations in Hungary, Spain and Norway, respectively. Other research projects include EINSTEIN (<https://www.einstein-project.eu/>), PITAGORAS (<https://pitagorasproject.eu/>) and SUNSTORE4 (<http://sunstore4.eu/use-results/sunstore4-tool/>), which provides a simple technical evaluation tool to dimensions seasonal storage and district heating systems. Another overview website is www.solar-district-heating.eu. Outside of Europe, the only seasonal storage plant known to the authors is at Drake Landing in Canada (Lanahan & Tabares-Velasco 2017).

ATES	30-40	50-90	Water	Varies	Varies
------	-------	-------	-------	--------	--------

The relatively high costs shown in this table are one reason why these systems are only suited to serve a settlement district consisting of several residential (and other buildings) – as a rule of thumb, systems should be above 1000 m³ (IEA 2015). These centralised systems do have lower specific costs than decentralised storages, though, which can lead to economic savings in the case of one centralised plant. A heat pump is an optional extra, as it means a higher utilisable temperature difference can be achieved as well as more efficient, smaller dimensions and better economics. Also heat pumps can make the whole system more economical, hence STES not only enables a higher fraction of solar heat to be integrated, it can also provide flexibility for CHP units, and utilize geothermal and waste heat sources. PTES systems can require a settling-in period of 3-5 years, hence in this paper only TTES is considered.

b. Literature review

Research with relevance to the analysis of seasonal thermal storage in the context of energy system modelling is outlined and assessed in the following. Table 2 summarizes the above mentioned studies with respect to selected key characteristic features.

Several authors have analyzed STES systems for individual residential buildings. For example, Antoniadis et al. (2018) examine the optimal design of a seasonal solar thermal energy storage system for a typical single-family detached home located in the urban context in Greece, within the TRNSYS modelling framework. Li et al. (2014) investigate an energy system comprised of a combined solar thermal heat pump system. They apply their TRNSYS model to a multi-family house type of dwelling in China, with an energy supply structure based on heat pump units as well as a solar collecting cycle and a seasonal storage tank. In addition, Ma et al. (2018) carry out a feasibility study of a 100% share of solar energy in the heat supply of a set of reference dwellings located in the UK. It is found that the envisioned goal of solar heat supply is achieved for the various use cases – partly requiring a larger than average available roof area of a detached house in the UK. Sweet et al. (2011) examine use cases of residential heat supply with the help of energy system modelling in TRNSYS. It is shown that auxiliary heat supply can be significantly substituted by the use of seasonal thermal storage, even to a higher degree with increasing storage capacity. Terziotti et al. (2012) investigate sand-based seasonal solar thermal energy storage in the context of heat supply of a multi-family house with TRNSYS, showing that a solar fraction of above 90% can be attained in an optimized energy system. Moreover, Haseraki et al. (2015) investigate an energy system comprised of a solar collector and heat pump complemented by a seasonal thermal storage embedded in a heating system of different temperature levels applied to a single-family house in Sweden over a full year time period. The authors find that system efficiency is highest for the maximum collector and storage size in combination with the lowest height to diameter across all heat systems of different temperature levels. Moreover, results prove best for the very low-temperature heat system. Finally, Zhang et al. (2015) implement an energy system model for greenhouse heating in China. The authors simulate a system comprised of solar collectors, a soil heat storage subsystem and a greenhouse heating system in TRNSYS. The study reveals that an additional seasonal thermal storage increases energy efficiency and reduces costs.

Other studies have analyzed STES for renewable heat integration at the district level. Hence McDaniel et al. (2016) create a TRNSYS model to a seasonal thermal energy storage system with combined-heat-power supplying a university campus. The authors conclude that a supply system integrating borehole thermal energy storage brings about a considerable cut in operating costs as well as emissions. Also, Paiho et al. (2017) perform a model-based energy system analysis of STES low energy buildings with solar thermal and heat pumps, at the residential district level in Finland. The energy system is

investigated with respect to self-sufficiency, emissions and remaining energy demand, and results point to an essential reduction of emissions as well as to a self-sufficiency in heat production of 60%. In addition, Semple et al. (2017) develop a model for a large scale solar collector system in combination with borehole thermal energy storage implemented in TRNSYS. The results imply a trade-off between the annual heating demand covered by solar energy and the corresponding levelized cost of the energy system. Furthermore, Sibbitt et al. (2012) analyze solar borehole seasonal storage in a use case of a community in Canada connected to solar-based district heating. The analysis relies on a two-stage process with a simulation tool (ESP-r) of energy demand followed by a TRNSYS model to determine the optimal size of the solar thermal collection area and the thermal storage. Results show that a required portion of approximately 100% of solar energy in heat demand can be attained by an optimized energy system at the end of the considered five year period. In addition, Hirvonen et al. (2018) analyze heat supply at the community level in Finland. The heat demand is simulated within the TRNSYS framework and the energy supply optimized in MOBO. The study shows that even in high latitude Nordic countries a significant fraction of winter heating can be provided by solar thermal energy.

Two studies are identified that focus on optimization², namely, Gabrielli et al. (2018) and Welsch et al. (2018). Gabrielli et al. (2018) investigate a polygeneration system with STES as well as hydrogen and electricity storage in a multi-energy system. The mixed integer linear programming method is applied to a residential multi-energy system at the neighborhood level, minimizing both total annual cost and emission of CO₂ in a multi-objective approach. The authors conclude that seasonal energy storage and operation is favored by the availability of a large amount of renewable generation, by a targeted significant reduction in CO₂-emissions and a high ratio of thermal to electrical demand. Similarly, Welsch et al. (2018) analyze an urban large-scale district heating system in the context of the residential and tertiary sectors. They develop an integrated assessment tool that is decomposed in a heating model, an economic model and a life cycle assessment. At the core of the methodology, a multi-objective optimization problem minimizes both the cost of heat and the emission of CO₂ equivalents with decision variables being the size of the solar collectors, the CHP and the seasonal thermal storage. It can be derived from the results that an optimized energy system comprised by a large solar collector area and seasonal thermal energy storage complemented by a small-dimensioned CHP plant proves most adequate in cost reduction and emission mitigation under both business as usual and policy evolution scenarios.

The foregoing discussion and the overview in Table 2 show that the investigated studies have a variety of regional foci as well as considered criteria, technologies and characteristics. Most studies are based on simulation and, if applicable, on a downstream heuristic approach based on the variation of key input parameters gearing towards improving the solution². However, only two studies are identified that use an optimization approach in the sense of mathematical optimization or Operational Research yielding a global optimum solution. Moreover, the development environment predominantly used for simulation is TRNSYS and the bandwidth of considered technologies is limited with a special focus on solar thermal collectors. Finally, the role of thermal storage is not always attributed a special focus of investigation which is due to the omission of sizing the seasonal storage capacity in a number of cases, as well as the inclusion of alternative thermal storage options – both of which might be considered decisive factors in attaining an optimized energy system. Neither of the discussed optimization studies has a focus on the model-based analysis of seasonal thermal storage at the neighborhood level using an optimizing modelling approach. Likewise, related research does not consider an exhaustive range of heat generating technologies and their competing effects. In addition, optimization in most cases

² The distinction between studies employing a heuristic and those using a mathematical optimization methodology as an area of Operational Research (as is used in this contribution), is not always clear-cut and therefore based on the authors' interpretation of the reviewed literature.

208 relates to technical criteria whereas other significant factors such as economic aspects and
209 dependency on external energy sources is generally not addressed.

210 In order to overcome the identified shortcomings in related research, the present work introduces a
211 modelling approach rooted in mixed integer linear programming that allows for an assessment of
212 energy systems at the neighborhood scale with a distinct focus on seasonal thermal storage in an
213 adequate way. The geographical scope is Germany as a representative country of Central Europe, a
214 region which has not yet been the focus of related research considered relevant up to now.

Table 2: Selected characteristic features of the investigated studies (x: considered, -: not considered, (-): unclear)

ST: solar thermal, GasB: gas boiler, CHP: combined heat and power, PV: photovoltaic, HP: heat pump

Study	Region	Sector	Considered criteria	Capacity planning/ sizing of technologies	Dispatch planning/ time resolution	Technologies	Sizing of seasonal thermal storage?	Level of technical detail	Methodology
Antoniadis et al. 2018	GR	Res	Cost	x	-	ST	x	low	Simulation (TRNSYS)
Gabrielli et al. 2018	CH	Res	Cost, CO ₂ -emission	x	x (hourly)	GasB, CHP, ST, PV	x	medium	MILP
Haseraki et al. 2015	SE	Res	Efficiency	x	-	ST, HP	x	low	Simulation (MATLB)
Hirvonen et al. 2018	FI	Res	Total electricity import, (life cycle) cost	x	monthly	ST, HP, PV	x	medium	Simulation (TRNSYS)
Li et al. 2014	CH	Res	Solar fraction in heating demand, system performance	x	x (hourly)	ST, HP	x	medium	Simulation (TRNSYS)
Ma et al. 2018	UK	Res	Solar fraction in heating demand	x	(x) (hourly)	ST	x	low	Simulation
McDaniel et al. 2016	US	Res	Cost, CO ₂ -/SO ₂ -/NO _x -emission	-	x (hourly)	CHP, gas turbine	-	medium	Simulation (TRNSYS)
Paiho et al. 2017	FI	Res	Local energy self-sufficiency, CO ₂ -/SO ₂ - /small particulate emission	x (only ST and PV)	-	ST, HP, PV	-	low	Simulation
Semple et al. 2017	CA	Ter	System efficiency, (levelised) cost	-	x (minutely)	ST, HP	-	Low	Simulation (TRNSYS)
Sibbitt et al. 2012	CA	Res	Solar fraction in heating demand, cost	x	x (day?)	ST, GasB	x		Simulation (TRNSYS)
Sweet et al. 2011	US	Res	Share of solar energy	x	-	ST	x	low	Simulation (TRNSYS)
Terziotti et al. 2012	US	Res	Share of solar energy	x	-	ST	x	low	Simulation (TRNSYS)
Welsch et al. 2018	DE	Res, Ter	Heating cost, Emission of CO ₂ equivalents	x	x	CHP, ST, GasB, HP	x	low	Optimization (Matlab)
Zhang et al. 2015	CH	Ter	Solar energy collection, electricity consumption, system cost	(-)	x	ST	(-)	medium	Simulation (TRNSYS)
This study	DE	Res	Cost, renewable heat fraction, CO ₂ emissions, renewable electricity fraction	x	x (hourly)	ST, HP, PV, GasB	x	medium	MILP (GAMS/Cplex)

3. Methodology

This section describes the employed methodology, starting with the existing POPART model (section 3.a), the extensions implemented within this paper (3.b), and key techno-economic assumptions and scenarios (3.c).

a. The POPART model

The employed model is an optimal capacity investment and dispatch planning approach for optimizing the energy system in residential buildings based on mixed integer linear programming. It is a deterministic, perfect foresight, cost minimization for the capacity investment and dispatch at hourly resolution for a residential building or group of buildings. The model is called POPART³ and was originally developed by Fehrenbach (2018) at the European Institute for Energy Research (EIFER) in Karlsruhe, Germany. It is similar to other models of this type, such as those employed elsewhere by Merkel et al. (2015) and McKenna et al. (2016). Given the focus of the present paper on seasonal storage technologies, the POPART model is only briefly introduced and relevant developments explained; a complete model description and validation can be found in Fehrenbach (2018).

The POPART model sets up a building's energy supply system for heat and power based on a minimal discounted system cost approach on a medium term time horizon of 20 years frequently employed in planning residential projects (Kunze 2015). It takes as input, inter alia, load profiles for heat and electricity, as well as a large number of techno-economic assumptions (cf. section 3.c below). The energy supply system is dimensioned and dispatched by adopting a greenfield approach (assuming no existing energy system is installed). The objective function to be minimized includes investment, fuel costs, maintenance costs, and revenues from renewable support mechanisms, for example for PV and micro CHP. Various constraints ensure, for example, that demand is always met, that a generator can only supply below or at its installed capacity, and that (only) allowed technologies may be installed. The POPART model is implemented in GAMS and solved using a CPLEX solver, essentially based on the branch-and-cut and simplex algorithms. The data input and output is organised with GAMS's GDX and/or Excel, and the model takes between a few minutes and several days to solve on a computer with a recent multicore x86 CPU clocked at 2.6 GHz equipped with 8 GB of RAM running GAMS version 23.9.5 with CPLEX version 12.4.0.1 on a Windows 7 operating system.

In terms of a brief overview, the POPART model can be formally described as follows.⁴ The objective is to minimize the total discounted energy expenditures Ξ^{tot} over a time horizon of years $y \in Y$ for all chosen technologies $t \in T$, composed of initial capacity investments Ξ_t^{inv} and operational expenditures $\Xi_{y,t}^{var}$ discounted to the base year at rate δ (cf. Eq. 1).

$$\min \Xi^{tot} = \sum_{t \in T} \Xi_t^{inv} + \sum_{y \in Y} (1 + \delta)^{-y} \sum_{t \in T} \Xi_{y,t}^{var} \quad (Eq. 1)$$

To include a basic representation of scale effects at a relatively low computational expense, the capacity investments Ξ_t^{inv} are modelled by a cost component proportional to the capacity κ_t at specific investments $\xi_t^{inv,m}$ (in €/kW) and a fixed investment portion $\xi_t^{inv,b}$ (in €) payable in case of a positive investment decision, modelled by the binary variable κ_t^{ind} , as indicated in Eq. 2.

$$\Xi_t^{inv} = \kappa_t \cdot \xi_t^{inv,m} + \kappa_t^{ind} \cdot \xi_t^{inv,b}, \quad \forall t \in T \quad (Eq. 2)$$

³ fr. *Programme d'Optimisation de l'Approvisionnement en Energie des Bâtiments Résidentiels*

⁴ For a detailed description of the POPART model the reader is referred to Fehrenbach (2018). Decision variables are represented in **bold** typeface.

This binary indicator variable κ_t^{ind} is constrained to 1 by Eq. 3 in case of an investment $\kappa_t > 0$ with M being a large positive number (in this case 1 million).

$$\kappa_t \leq \kappa_t^{ind} \cdot M, \quad \forall t \in T \quad (Eq. 3)$$

The variable expenditures $\Xi_{y,t}^{var}$ are composed of expenditures for final energy carriers, other operation and maintenance expenditures less revenues from electricity sales and support instruments on injected or self-consumed electricity. For instance, the expenditures for final energy carriers $\Xi_y^{fin,tot}$ are calculated as shown in Eq. 4 as the product of the activity variable $\alpha_{h,t,y}$ and the energy rate $\xi_{t,y}^{fin}$ in all hours of the year $h \in H$.

$$\Xi_y^{fin,tot} = \sum_{t \in T} \sum_{h \in H} \alpha_{h,t,y} \cdot \xi_{t,y}^{fin}, \quad \forall y \in Y \quad (Eq. 4)$$

The main constraints include a balance of generation and use for both energy carriers $u \in U = \{el, th\}$ electricity (*el*) and heat (*th*) in Eq. 5, demand satisfaction in every hour in Eq. 6 and a capacity restriction in Eq. 7⁵.

$$\alpha_{h,t} \cdot \eta_{t,u} = \alpha_{h,u,t}^{fit} + \alpha_{h,u,t}^{st,i} + \alpha_{h,u,t}^{dir} + \alpha_{h,u,t}^{hp}, \quad \forall h \in H, \forall u \in U, \forall t \in T \quad (Eq. 5)$$

$$\sum_{t \in T} \alpha_{h,u,t}^{dir} + \alpha_{h,u}^{st,o} = \lambda_{h,u} \cdot A_u, \quad \forall h \in H, \forall u \in U \quad (Eq. 6)$$

$$\alpha_{h,t} \leq \kappa_t, \quad \forall h \in H, \forall t \in T \quad (Eq. 7)$$

As a crucial element for this paper, storage is modelled by a storage balance equation (Eq. 8), a description of storage losses by a cycle efficiency (Eq. 9) and a storage capacity restriction (Eq. 10)⁶.

$$\chi_{h+1,u} = \chi_{h,u} - \alpha_{h,u}^{st,o} + \sum_{t \in T} \alpha_{h,u,t}^{st,i} - \alpha_{h,u}^{st,loss}, \quad \forall h \in H, u \in U \quad (Eq. 8)$$

$$\alpha_{h,u}^{st,loss} = (1 - \eta_u^{st}) \cdot \sum_{t \in T} \alpha_{h,u,t}^{st,i}, \quad \forall h \in H, \forall u \in U \quad (Eq. 9)$$

$$\chi_{h,u} \leq \kappa_u^{st}, \quad \forall h \in H, \quad \forall u \in U \quad (Eq. 10)$$

Eq. 11 links the activity of heat pumps $\alpha_{h,hp}$ to their electricity consumption $\alpha_{h,el,t}^{hp}$ which enables electric self-consumption (e.g. from PV) in heat pumps (cf. Eq. 5).

$$\alpha_{h,hp} = \sum_{t \in T} \alpha_{h,el,t}^{hp}, \quad \forall h \in H \quad (Eq. 11)$$

Further diverse constraints apply. For example, Eq. 5 constrains the operation of solar thermal plants based on a profile obtained from SoDa (2012). For a more detailed description of the base version of the POPART model the reader is referred to Fehrenbach (2018).

⁵ where $\eta_{t,u}$:= conversion efficiency, $\alpha_{h,u,t}^{fit}$:= grid injections, $\alpha_{h,u,t}^{st,i}$:= storage input, $\alpha_{h,u,t}^{dir}$:= direct consumption, $\alpha_{h,u,t}^{hp}$:= heat pump electricity, $\alpha_{h,u}^{st,o}$:= storage output, $\lambda_{h,u}$:= load profile, A_u := peak load

⁶ where $\chi_{h,u}$:= state of charge, $\alpha_{h,u}^{st,loss}$:= storage losses, η_u^{st} := storage cycle efficiency, κ_u^{st} := storage capacity

b. Extensions to POPART in this paper

The basic version of POPART as presented above and documented in detail in Fehrenbach (2018) was modified for application in the present contribution. In particular, these modifications relate to the modelling of seasonal storage technologies and the updating of techno-economic assumptions. In a first step, a STES system was implemented with techno-economic assumptions as given below in Table 3. The STES has the same mode of operation as a short-term thermal energy storage, but obviously differs in its technical and economic characteristics. To store energy across the seasonal time horizon, a low self-discharge rate is essential. Whereas in the base version of the POPART model, storage losses were modelled exclusively by a cycle efficiency, for the application in this paper a distinction between cycle losses at efficiency $\eta_u^{st,cy}$ ($\frac{kWh_{out}}{kWh_{in}}$) and self-discharge losses at rate $\eta_u^{st,sd}$ (h^{-1}) was added by modifying Eq. 9 as shown in Eq. 12.

$$\alpha_{h,u}^{st,loss} = (1 - \eta_u^{st,cy}) \cdot \sum_{t \in T} \alpha_{h,u,t}^{st,i} + \eta_u^{st,sd} \cdot \chi_{h,u}, \quad \forall h \in H, \forall u \in U \quad (Eq. 12)$$

The second step in the STES implementation was to define a constraint on the amount of renewable heat supplied. This was achieved by representing the fraction of renewable heat supply RES_h in total heat demand as in Eq. 13 and then constraining RES_h to a minimum level RES_h^{min} as in Eq. 14 (cf. Table 4). Eq. 13 relates the heat generation from solar thermal and heat pump to the total heat demand.

$$RES_h = \frac{\sum_h \alpha_{h,solth} \cdot \eta_{solth,th_p} + \sum_h \alpha_{h,el,elpur}^{hp} \cdot Grid_{RE} \cdot \eta_{htpmp,th_p} + \sum_h \alpha_{h,el,pv}^{hp} \cdot \eta_{htpmp,th_p}}{\sum_h \lambda_{h,th} \cdot \Lambda_{th}} \quad (Eq. 13)$$

$$RES_h \geq RES_h^{min} \quad (Eq. 14)$$

In Eq. 13, $Grid_{RE}$ represents the renewable fraction of grid electricity, which is defined as 30% in 2015 (BMWi 2017), the base year and expected to vary in the future (cf. Table 4). Therefore, $\sum_h \alpha_{h,solth} \cdot \eta_{solth,th_p}$ represents the annual solar thermal generation, $\sum_h \alpha_{h,el,elpur}^{hp} \cdot Grid_{RE} \cdot \eta_{htpmp,th_p}$ the heat pump output based on grid electricity, $\sum_h \alpha_{h,el,pv}^{hp} \cdot \eta_{htpmp,th_p}$ the heat pump output based on self-consumed electricity from PV, and $\sum_h \lambda_{h,th} \cdot \Lambda_{th}$ the total annual heat demand (cf. Eq. 6).

In addition, the endogenous calculation of the energy systems' (direct) CO₂ emissions was implemented in the model. The grid CO₂ intensity and renewable energy fraction are linked by a linear relationship, from 0.624 kgCO₂/MWh and 30% respectively today (BMWi 2017), falling to 0 kgCO₂/MWh and 100% respectively at some uncertain time in the future.

Further extensions related to the available area for the installation of PV and/or solar thermal technologies. The total roof area in the model was represented and constrained, whereby these two technologies can be built in fixed proportions up to and including the total available area. The employed power densities for this purpose are given in Table 3 below. In addition, the load profiles were adapted (cf. following section) in order to account for modern new-build dwellings of a high energetic standard.

c. Assumptions, demand case and scenarios

The majority of the techno-economic assumptions for the technologies analyzed in this paper have been taken from technology databases such as the Energy Database (www.energie-datenbank.eu), which contains detailed data for solar thermal plants, heat pumps, batteries and hot water storage

tanks. The assumptions relating to seasonal storage technologies were mainly adopted from two sources, namely the PhD Dissertation “Economic Feasibility of Seasonal Thermal Storage” (Schmuck 2017) and publications in the context of the IEA’s Task 45 on Large Scale Solar Heating and Cooling Systems (e.g. IEA 2015). An overview of the techno-economic assumptions extracted from these sources and employed within the POPART model for this paper is given in Table 3 below. In addition, the energy-political framework for renewable technologies is considered in the form of the Renewable Energy Sources Act 2014 and the Combined Heat and Power Act 2016, both of which regulate the remuneration levels for electricity from PV and CHP systems. For further details of these laws and their implementation in POPART, the reader is referred to Fehrenbach (2018).

Table 3: Overview of techno-economic assumptions for the considered technologies

Technology	Investment and installation (€)	Capacity specific investment (€/kW or €/kWh)	O&M Costs (€/kWh)	Fuel costs (€/kWh)	Efficiency (%)	Self-discharge rate (1/h)	Power density (kW/m ²)
Gas mCHP	8,000	5,000	0.007	0.069	0.92 ⁷	n/a	n/a
Gas boiler	3,301	55	0.010	0.069	0.95	n/a	n/a
Solar thermal	50	800	0.005	0	0.75	n/a	0.5
PV	3,159	1,351	0.020	0	0.83	n/a	0.1
Heat pump	2,961	572	0	0	2.60	n/a	n/a
Grid electricity	0	0	0	0.291	1.00	n/a	n/a
Seasonal thermal storage (TTES)	154,072	1.5	0	0	0.75	0.00001	n/a
Battery	170	1,209	0	0	0.85	0.00003	n/a

In the context of this paper, a typical new-build residential quarter is analyzed consisting of 50 Multiple Family Houses (MFHs). The load profiles for these buildings for space heating, hot water and electricity, are provided by the SynPRO stochastic multi-energy simulation model in an hourly resolution for one year (Fischer et al. 2015). Each building has 35 inhabitants in 10 apartments, whereby the allocation of socioeconomic household types to each apartment occurs at random in order to represent an ‘average’ household structure. The new building (period 2001 to 2016) has an annual space heating and hot water demand for space heating of around 69.7 MWh/a, which corresponds to an insulation standard of 54 kWh/m² a_{floor area}, and about 39.7 MWh/a electricity demand. Hence the residential quarter of 50 MFHs, with a total floor area of 64,500 m² has total heat and electricity demands of 3,483 MWh/a and 1,984 MWh/a respectively.

Runs of the POPART optimization model are performed within a scenario framework that is designed to derive a range of insightful results. Therefore, five scenarios are defined which are set out in Table 4. The logic behind these scenarios is to cover a range of feasible current and future configurations for the analyzed residential district. The first, reference scenario represents the situation today, whereby the renewable fraction of grid electricity is about 30%, there are no constraints on RES_h and the investment in the STES as well as the gas price are as shown in Table 3. The second scenario, ‘High RES_h today’, differs from the first only in the minimum RES_h value of 60%, thus reflecting a situation in which, under current framework conditions, the (required) renewable heat fraction is drastically increased. The scenarios 3 to 5 represent possible situations in 2030, hence all having 60% renewable grid electricity in accordance with German national targets (BMWi & BMU 2010). The third is also similar to the reference scenario, but with a 20% lower STES investment and a 20% higher gas price. Scenario four is characterised by a high gas price (150% compared to the level of

⁷ 0.22 electrical, 0.70 thermal

Table 3) with no constraints on RES_h , and scenario five reaches a RES_h of 100%. The assumed gas price increase in scenario 3 of 20% corresponds to an annual increase of 1.4% which is in line with scenario assumptions in literature (e.g. IEA 2018 p. 174 for wholesale prices or Schlesinger et al. 2014 p. 73 for German household consumer retail prices). The assumed gas price increase in scenario 4 of 50%, corresponding to 3.2% p.a., serves to analyze the effects of a pronounced price increase, as observed in Germany in the period of 2002 to 2015, for example, with natural gas retail prices for household consumer increasing by 3.5% p.a. over that period (BMWi 2018 p. 26).

Table 4: Overview of the five analyzed scenarios, which differ according to values of $Grid_{RE}$, RES_h , the investment in the STES and the gas price

	1	2	3	4	5
Scenario name / Parameter	Reference	High RES_h today	80pc invest SS_120pc gas price_2030	No constraints_high gas price_2030	Very high RES_h 2030
$Grid_{RE}$	0.3	0.3	0.6	0.6	0.6
Lower bound on RES_h	0.0	0.6	0.0	0.0	1.0
Invest_SS	100%	100%	80%	100%	100%
Gas price	100%	100%	120%	150%	100%

4. Results and discussion

a. Validation and plausibility-check of results

Figure 1 shows the model results in scenario 3 alongside data from eleven pilot projects implemented in Germany (the installed capacities in this scenario are in Figure 3).

Figure 1: Validation of the model results with data from 11 German pilot projects (Source: Solites 2012)

Shown are the ratios of collector area to heat demand and heated floor area, as well as that of STES volume to collector area. Overall, the POPART results are in good agreement with those from the pilot projects. The ratio of installed collector area to heated floor area is relatively small in the POPART results, due to the fact that, in this scenario, around 2/3 of the heat is supplied by a gas boiler. In comparison, the pilot projects are typically conceptualized to have a much higher

renewable heat supply fraction, mainly based on solar thermal plant, with additional heat pumps in some cases. Scenarios 2, 4 and 5 all have much higher RES_h values, but are not comparable due to the lack of substantial solar thermal capacity. Hence we conclude that the system specification as dimensioned here is technically realistic and feasible.

Figure 2 below shows the dispatch of the optimized energy system from scenario 3 in the course of the analyzed model year. On the left axis the direct heat supply from solar thermal and the gas boiler, as well as the heat demand, can be read. On the right hand axis, the storage level of the seasonal storage is shown. The employment of the STES to shift the heat, especially from the solar thermal system, from summer into winter, is clearly visible. The gas boiler is used alongside the thermal storage system in winter to meet (peak) demand. Note that only the direct supply from gas or ST is depicted here; loading or unloading the storage is not shown and the figure shows mean values for any given day, both of which explains the gap between shown direct supply and the demand curve. Overall, then, Figure 2 shows that the POPART model is working as intended and employing the newly-implemented STES systems for their intended purpose.

Figure 2: Temporal structure of heat supply and seasonal storage fill level from scenario 3

b. Comparison of the scenarios

The optimal energy system capacities for the five analyzed scenarios are shown in Figure 3 below. The energy supply technologies are shown on the left hand axis and the STES on the right hand side. In the reference scenario, as expected, the energy system is dominated by a gas boiler, with smaller capacities of ST and PV, and no heat pump or STES installed respectively. The achieved value of RES_h in this scenario is just 0.03 (cf. Figure 5), which is due to the dominance of gas for heat supply. In the second scenario, the constraint of 60% RES_h requires a drastically different configuration. The gas boiler capacity is reduced to around 1 MW, a 0.5 MW heat pump is installed, and both PV and ST systems are significantly larger. In this scenario, also a STES system with around 20 MWh capacity is selected by the model. The still relatively small capacity of the STES is accounted for by the overall

quite modest value of RES_h (60%) as well as the fact that the heat pump can be used flexibly to supply heat at any time of the year.

Moving on to the three 2030 scenarios (3-5, all with $Grid_{RE} = 60\%$), here more significant changes can be seen in the energy systems. The third scenario, with 80% specific investment in the STES and 120% gas price compared to the reference case, has the largest solar thermal and STES capacities, of about 1.7 MW and 70 MWh respectively. In addition, a modest capacity of PV but no heat pump are installed. The RES_h value in this scenario is 0.29. In contrast, the fourth scenario, with an even higher gas price (150% compared to the reference scenario), has only PV (2.2 MW) and a heat pump (0.7 MW) in the solution, with a STES of about 15 MWh and RES_h of 0.76. Finally, the fifth scenario, with 100% RES_h , has substantially larger capacities of PV (4 MW) and heat pump (1.3 MW), in this case supplemented by about 0.5 MW gas boiler. The latter is installed to account for the fact that RES_h is applied to generation before storage, in other words to make up for the efficiency and storage losses of heat generated from the heat pump. Analysing the dispatch profile for this scenario, not shown here for brevity, reveals that the gas boiler is employed as a peaking device, when the heat demand is at its highest and the STES is almost empty.

Figure 3: Overview of installed capacities in the five analyzed scenarios

Moving on to examine the costs in the five scenarios, Figure 4 shows the total system costs and respective proportions. Overall, the total discounted system costs are in the range from € 7.4 million to € 8.4 million, i.e. with an increase of up to about 14% compared to the reference scenario. This relatively modest difference in the total costs overlooks some rather drastic differences in the cost structure between scenarios. Whereas the reference scenario has the highest proportion of fuel costs, at € 6 million or 81%, due to the heavy reliance on gas supply, the other scenarios have lower fuel costs but (much) higher investments. Especially the scenarios with (larger) RES_h values and STES installed also have a substantially higher investment: the fifth scenario with 100% RES_h even has 7.5 € million or 89% investment as a fraction of overall costs. Also correlated with the value of RES_h is the level of the revenue from renewable support mechanisms. These revenues account for about 10%

and 30% of the total costs in scenarios two and five respectively, hence significantly reducing the overall cost. Finally, and as expected, the maintenance costs are relatively low compared to the overall costs.

Under the current energy-political framework conditions, a renewable heating fraction of 60% (compared to 3% in the reference scenario) could be achieved with additional costs of just € 0.1 million or 1%. It is also interesting to note what a strong effect small variations in the assumptions have for the three 2030 scenarios. Especially the third scenario, with only 20% variations in STES investment and gas prices respectively, seems to confirm the assertion made in section 2 above, that STES are on the verge of making a market breakthrough and becoming competitive. Especially in combination with solar thermal, in the case of this scenario, the STES could be a promising opportunity to integrate higher levels of renewable heat into the residential energy supply system. Although not analyzed here, the results of scenario four, whereby gas investment is completely avoided with a 150% gas price compared to the reference scenario, a similar scenario combined with an 80% STES investment could be interesting. The avoidance of gas investment altogether might lead to an even higher STES capacity, especially if the heat pump is still not employed as in scenario 3.

Figure 4: Overview of total costs and the respective fractions in the five analyzed scenarios

Despite scenario 5 having the overall highest level of RES_h (1) and the lowest CO_2 emissions (0.24 Mt), it also has the highest cost (Figure 5). Both scenarios 2 and 4 also have high CO_2 savings compared to the reference scenario (i.e. 0.6 Mt compared to 1.2 Mt), but at a lower cost (especially in scenario 2) and only moderately reduced RES_h value of 60-75%. Hence from the perspective of reconciling all three criteria, scenario 2 would seem to be the 'best', in terms of most robust, solution (see Figure 5). But there is a trade-off between increasing the renewable heat supply fraction RES_h and the associated system cost, as also found by Semple et al. (2017). Another way of expressing this conclusion is that the last approx. 20% renewable heat supply and/or CO_2 emissions abatement is associated with very high costs compared to the achieved approx. 80%. Particularly in the context of emission saving measures in residential buildings, both the supply side as analyzed here and the

demand side (i.e. through insulation measures) have a role to play. Hence there is a strong argument for combining both approaches and therefore not opting for the more extreme scenarios considered here, but instead aiming for modest fractions of renewable heating such as 60-80%.

Figure 5: Costs, CO₂ emissions and renewable heat fraction for the five scenarios

Overall, then, the results show that STES could make a substantial contribution to increasing RES_h in the residential sector, both today at slightly higher costs than the alternative and in the future even at similar or lower costs than the alternatives. These findings are similar to those of Welsch et al. (2018), who show that the most cost-effective CO₂ emissions reductions are achieved by a combination of solar thermal, STES and a peaking plant, which in their study is a CHP unit and in the present case a gas boiler. A further comparison with Gabrielli et al. (2018) is not made due to that study's (additional) consideration of hydrogen generation and storage.

c. Parameter/sensitivity analysis

In the context of carrying out this work, some clear interdependencies between specific model settings was encountered. This applies especially to the assumed maximum collector area, and to some extent to the factor Grid_{RE}, and their implications for the configuration of the optimized energy system. Whilst not shown here for brevity, the choice of energy system for a given parameter configuration varies significantly. The maximum collector area is a hard constraint, so that for certain high values of RES_h the problem becomes infeasible when relying on solar thermal. In addition, the choice of a heat pump to supply renewable heat becomes more attractive with higher fractions of renewable electricity from the grid. These framework conditions represent important characteristics for a given residential district when analyzing the suitability of renewable energy systems, hence why they are shown in Figure 6.

From the figure, it is clear that particularly large seasonal storages are installed to achieve high RES_h values in combination with lower Grid_{RE} values (i.e. 0.3) and higher available collector areas. Under

these framework conditions solar thermal technology is favoured over heat pumps, and therefore requires the large storage capacities. At lower values of the maximum collector area and higher $Grid_{RE}$ values respectively, the optimal solution becomes dominated by heat pumps, which alleviates the requirement for such large seasonal storage capacities. One implication of these results is that, as the renewable fraction of the grid electricity increases and with a constrained available area, the relative attractiveness of employing heat pumps alongside or instead of solar thermal technologies increases. If the area is not constrained, then solar thermal is still the most economical option, but the size of the required seasonal storage system will still decrease in the future due to the synergy effects of employing solar thermal alongside heat pumps. The key point is that a higher $Grid_{RE}$ results in, ceteris paribus, a lower required STES capacity due to the combination with a heat pump, which can make a relatively larger contribution to RES_h (Eq. 13).

Further sensitivity analyzes were carried out to analyze the effect on the results of small variations of the model assumptions. In particular, the focus in these analyzes was on the gas and electricity prices, as well as the techno-economic assumptions relating to central technologies (i.e. seasonal storage). Broadly speaking, these sensitivity analyzes confirmed expectations, and for this reason are only briefly reported here. The gas price has one of the strongest effects, as already demonstrated in two of the five scenarios. A higher gas price therefore discourages investment in gas boilers and, ceteris paribus, a shift to PV and/or heat pumps (cf. Figure 3). Similarly for the electricity price, an increase of about 30% results in a higher investment in PV, in order to reduce electricity demand from the network. Finally, the seasonal storage investment decision is also very sensitive to the employed assumptions. As shown in Figure 6, even with the reference assumptions for the seasonal storage (cf. Table 3), a modestly sized unit is installed in the cases with large collector areas, $Grid_{RE}$ of 0.3 and low (i.e. 0) values of RES_h .

Figure 6: Sensitivity of the installed STES capacity to the assumed values of the maximum collector area, the $Grid_{RE}$ and the achieved RES_h

d. Discussion of the method and further work

This section discusses the employed method and suggests some areas for further work. Firstly, there are several general and well-known weaknesses associated with linear programming approaches such as this one. Amongst the most relevant in the present case is the perfect foresight and the associated optimization of the energy system for a representative year for the lifetime of the project. Clearly the approach is also subject to a moderate level of uncertainty, which is only partly removed through the parameter/sensitivity analysis. The POPART model requires a large amount of input data from many different sources, including techno-economic specifications, irradiation profiles, demand profiles for heat and power, evolution of fuel prices etc. The energy-political framework conditions for renewable electricity generation are considered, but those relating to renewable heating (such as investment grants or loans) are not. Whilst we have endeavoured to ensure that these data are accurate and up to date, their impact on the results is obviously strong and it is not feasible to explore all of the feasible solution space or all possible combinations of input data.

Also, the POPART model has a degree of abstraction from technical details concerning the operation of energy technologies. This means that, for example, the heat pump and the gas boiler are able to ramp up and down extremely quickly and without constraints. In reality, of course, there are technical limitations: not only do these devices require time to ramp up and down, this also has an adverse effect on their operational lifetime, thereby increasing the running costs. But for this energy system analysis of a residential district these details are not indispensable. On the other hand, the implication is that the dimensioned systems and their operation are subject to a degree of ambiguity, such that the work should be understood as more of a scoping study rather than a detailed planning one. For this reason also the absolute results presented here should be interpreted with caution; the focus lies more on the relative differences in results between different framework conditions, as considered through the individual scenarios. A detailed planning study for any of these scenarios would no doubt reveal significant differences in the absolute results.

Hence future work should try to improve the modelling approach to deal with some of the abovementioned weaknesses, for example by improving the ramping behaviour of energy technologies (which could be especially important in the context of flexibility) and incorporating different irradiation and demand profile sets. In addition, the formulation of the RES_h constraint should be improved to consider storage losses, rather than purely focussing on generation. The relationship between the grid renewable electricity fraction and the optimal renewable heat integration strategy, also in the context of a limited collector area as shown in Figure 6, could also be explored in future work.

Whilst the original motivation behind this study centred around integrating more renewable heat into decentralized energy systems, there are also numerous other avenues of work which could be explored. For example, the issue of security of supply has been extensively analyzed in the context of centralized energy systems, but less so for decentralized ones. Based on reliability data for the employed technologies, future work might analyze the implications for security of supply of such a decentralized energy system, for example depending largely on solar irradiation and seasonal storage for its heat supply. This would provide an additional criterion with which to assess these energy storage technologies in the context of the energy transition.

5. Summary, conclusion and outlook

Against the background of low fractions of renewable heat in residential heat supply, this paper set out to economically and technically assess the possible contribution of seasonal thermal energy storage (STES). By extending an existing mixed integer linear program to consider STES, the energy

system for a typical German residential district with efficient new-build apartment buildings was optimized in the context of five scenarios. As expected, achieving much higher fractions of renewable heat supply requires significant capacities of seasonal storages and is associated with a higher cost than in the reference scenario. However, this cost is only substantially (14%) higher in the context of a scenario with 100% renewable heat supply. In less extreme scenarios, for example to achieve a 60% renewable heat supply fraction under today's framework conditions, the cost increase is marginal (1%). Further intermediate scenarios showed the potential impact of a reduction in costs for the STES systems as well as an increase in the gas price, or both.

The results in these scenarios demonstrate that even higher levels of renewable heat supply can become economically attractive without being forced into the solution. Clearly there are trade-offs between the results and costs are by far not the only criteria. Indeed, an examination of the further criteria of CO₂ emissions in these five scenarios reveals the conflicting nature of the results. The implication is that very high levels of renewable heat supply would not necessarily be recommended due to the high cost. Instead, levels of around 60-80% could and should be strived for, which, in combination with further demand side measures (such as insulation, not considered here), stand to achieve similar emissions savings at a lower cost.

The employed method and the assumptions are clearly subject to substantial uncertainties, which means the results should be treated with caution. Especially the perfect foresight and the adoption of static profiles for irradiation and demand, as well as the relatively rough depiction of the technologies, mean that this study is not intended as the basis for energy system planning. Much more, it is intended to explore the interrelationship between macroeconomic (grid emissions factor, fuel prices) and microeconomic (collector area, renewable heat fraction) parameters on the optimal decentralized energy system for a typical residential district. Especially the revealed interdependencies between these aspects, for example the way the collector area influences the optimal supply system, therefore represent some of the key insights.

Hence one area of further work should focus on improving the level of detail in the technical modelling, as well as incorporating different irradiation and demand profile sets. Another would be to more systematically explore the relationship between the grid renewable electricity fraction and the optimal renewable heat integration strategy, also in the context of a limited collector area as shown in Figure 6, in more detail. Finally, the issue of security of supply has been extensively analyzed in the context of centralized energy systems, but less so for decentralized ones. Based on reliability data for the employed technologies, future work might analyze the implications for security of supply of such a decentralized energy system, for example depending largely on solar irradiation and seasonal storage for its heat supply.

6. Acknowledgements

This work was partly carried out in the context of the 'LowEx-Bestand' project (<http://www.lowex-bestand.de/?lang=de>), funded by the BMWi with grant number 03SBE0001A/B/C, as well as the Smart City Accelerator project (<https://smartcitiesaccelerator.eu/about-smart-cities-accelerator/>). The authors are grateful to two referees for their helpful comments on an earlier version of this paper. The usual disclaimer applies.

7. References

- Antoniadis, C.N.; Martinopoulos, G. (2018): Optimization of a building integrated solar thermal system with seasonal storage using TRNSYS. Renewable Energy. DOI: 10.1016/j.renene.2018.03.074
- BMWi (Bundesministerium für Wirtschaft und Technologie) (2017): Renewable Energy Sources in Figures: National and International Development, 2016, https://www.bmwi.de/Redaktion/EN/Publikationen/renewable-energy-sources-in-figures-2016.pdf%3F__blob%3DpublicationFile%26v%3D5, checked 18.10.18.
- BMWi (2018): Zahlen und Fakten, Energiedaten – Nationale und Internationale Entwicklung. Compilation of energy related statistics issued by the German Federal Ministry of Economics (BMWi).
- BMWi (Bundesministerium für Wirtschaft und Technologie) & BMU (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit), 2010. Energiekonzept der Bundesregierung: für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung, 28. September 2010. https://www.bmwi.de/Redaktion/DE/Downloads/E/energiekonzept-2010.pdf?__blob=publicationFile&v=3 (accessed 13 September 2018).
- De Groote, M., & Rapf, O. (2015). The active role of buildings in a transforming energy market. Discussion paper. Brussels: Buildings Performance Institute Europe (BPIE).
- Eurostat. (2018). Renewable energy statistics, https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics, checked 18.10.18.
- Fehrenbach, D. (2018): Modellgestützte Optimierung des energetischen Eigenverbrauchs von Wohngebäuden bei sektorgekoppelter Wärmeversorgung - Vorstellung des POPART-Modells, Production and Energy, Nr. 32, ISSN 2196-7296, <https://www.iip.kit.edu/2117.php>, checked 18.10.18.
- Fischer, D. et al. (2015): Model for electric load profiles with high time resolution for German households, Energy and Buildings, 92, 170-179.
- Gabrielli, P.; Gazzani, M.; Martelli, E.; Mazzotti, M. (2018): Optimal design of multi-energy systems with seasonal storage. Applied Energy, DOI: 10.1016/j.apenergy.2017.07.142
- Haseraki, A.; Halilovic, A.; Holmberg, S. (2015): Low-temperature heat emission combined with seasonal thermal storage and heat pump. Solar Energy, 119, 122-133. DOI: 10.1016/j.solener.2015.06.046
- Hirvonen, J.; Rehman, H.; Sirén, K. (2018): Techno-economic optimization and analysis of a high latitude solar district heating system with seasonal storage, considering different community sizes. Solar energy, 162, 472-488. DOI: 10.1016/j.solener.2018.01.052
- IEA (2015): Seasonal thermal energy storage: Report on the state of the art and necessary further R&D, Solar Heating and Cooling Programme, Task 45 Large Systems, Ed. Dirk Mangold and Laure Deschainre, Solites Stuttgart.
- IEA (2018): World Energy Outlook. Report of the International Energy Agency, Paris. ISBN: 978-92-64-30677-6
- Kunze, R. (2015): Techno-ökonomische Planung energetischer Wohngebäudemodernisierungen : Ein gemischt-ganzzahliges lineares Optimierungsmodell auf Basis einer vollständigen Finanzplanung, PhD Thesis at KIT, Karlsruhe, Germany, <https://publikationen.bibliothek.kit.edu/1000052701>.

420 Lanahan, M., Tabares-Velasco, P. C. (2017): Seasonal Thermal-Energy Storage: A Critical Review on
 421 BTES Systems, Modeling, and System Design for Higher System Efficiency, *Energies* 2017, 10, 743;
 422 DOI:10.3390/en10060743.

423 Li, H.; Sun, L.; Zhang, Y. (2014): Performance investigation of a combined solar thermal heat pump
 424 heating system. *Applied Thermal Engineering*, 71, 460-468. DOI:
 425 10.1016/j.applthermaleng.2014.07.012

426 Ma, Z.; Bao, H.; Roskilly, A.B. (2018): Feasibility study of seasonal solar thermal energy storage in
 427 domestic dwellings in the UK. *Solar Energy*, 162, 489-499. DOI: 10.1016/j.solener.2018.01.013

428 McDaniel, B.; Kosanovic, D. (2016): Modeling of combined heat and power plant performance with
 429 seasonal thermal energy storage. *Journal of Energy Storage*, 7, 13-23. DOI: 10.1016/j.est.2016.04.006

430 McKenna, R., Bertsch, V., Mainzer, K., Fichtner, W. (2018): Combining local preferences with multi-
 431 criteria decision analysis and linear optimisation to develop feasible energy concepts in small
 432 communities, *European Journal of Operational Research*, Volume 268, Issue 3,
 433 <https://doi.org/10.1016/j.ejor.2018.01.036>

434 McKenna, R., Merkel, E., Fichtner, W. (2016): Energy autonomy in residential buildings: a techno-
 435 economic model-based analysis of the scale effects, *Applied Energy*, 189, 800-815,
 436 <http://dx.doi.org/10.1016/j.apenergy.2016.03.062>.

437 Merkel, E., McKenna, R., Fichtner, W. (2015): Optimisation of the capacity and the dispatch of
 438 decentralised micro-CHP systems: a case study for the UK, *Applied Energy*, 140, 120-134.

439 Paiho, S.; Hoang, H.; Hukkalainen, M. (2017): Energy and emission analyses of solar assisted local
 440 energy solutions with seasonal heat storage in a Finnish case district. *Renewable Energy*, 107, 174-
 441 155. DOI: 10.1016/j.renene.2017.02.003

442 Schlesinger, M.; Lindenberger, D.; Lutz, C. et al. (2014): Entwicklung der Energiemärkte –
 443 Energiereferenzprognose. Final report of a study by a research consortium headed by Prognos AG
 444 commissioned by the German Federal Ministry of Economics (BMWi).

445 Schmuck, M. (2017): Wirtschaftliche Umsetzbarkeit saisonaler Waermespeicher, Schriftenreihe des
 446 Instituts fuer Baubetriebswesen der Technischen Universitaet Dresden, Expert Verlag, Renningen.

447 Semple, L.; Cariveau, R.; Ting, D. (2017): A techno-economic analysis of seasonal thermal energy
 448 storage for greenhouse applications. *Energy and Buildings*, 154, 175-187. DOI:
 449 10.1016/j.enbuild.2017.08.065

450 Sibbitt, B.; McClenahan, D.; Djebbar, R.; Thornton, J.; Wong, B.; Carriere, J.; Kokko, J. (2012): The
 451 performance of a high solar fraction seasonal storage district heating system – five years of
 452 operation. *Energy procedia*, 30, 856-865. DOI: 10.1016/j.egypro.2012.11.097

453 SoDa (2012): Time Series of Solar Radiation Data (HelioClim3) – Solar radiation data online service.
 454 Onlinedienst von MINES ParisTech zur solaren Einstrahlungsdaten. Checked in 2012 from
 455 http://www.soda-is.com/eng/services/services_radiation_pay_eng.php

456 Solites (2012): Technisch-Wirtschaftliche Analyse und Weiterentwicklung der Solaren Langzeit-
 457 Waermespeicherung, Wissenschaftlich-technische Programmbegleitung fuer
 458 SOLARTHERMIE2000PLUS, Forschungsbericht zum BMU Vorhaben 0329607N.

459 Sweet, M.L.; McLeskey Jr., J.T. (2012): Numerical simulation of underground Seasonal Solar Thermal
 460 Energy Storage (SSTES) for a single family dwelling using TRNSYS. Solar Energy, 86, 289-300. DOI:
 461 10.1016/j.solener.2011.10.002

462 Terziotti, L.T.; Sweet, M.L.; McLeskey Jr., J.T. (2012): Modeling seasonal solar thermal energy storage
 463 in a large urban residential building using TRNSYS 16. Energy and Buildings, 45, 28-31. DOI:
 464 10.1016/j.enbuild.2011.10.023

465 Welsch, B; Göllner-Völker, L.; Schulte, D.O.; Bär, K.; Sass, I.; Schebeck, L. (2018): Environmental and
 466 economic assessment of borehole thermal energy storage in district heating systems. Applied Energy,
 467 216, 73-90. DOI: 10.1016/j.apenergy.2018.02.011

468 Zhang, L.; Xu, P.; Mao, J.; Tang, X.; Li, Z.; Shi, J. (2015): A low cost seasonal solar soil heat storage
 469 system for greenhouse heating: Design and pilot study, Applied Energy, 156, 213-222. DOI:
 470 10.1016/j.apenergy.2015.07.036

471

472