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Seasonal thermal energy storage in smart energy systems: District-level applications and modelling approaches

Lyden, A.[a,*], Brown, C.S.[b], Kolo, I.[b], Falcone, G.[b] and Friedrich, D.[a]

[a] School of Engineering, Institute for Energy Systems, University of Edinburgh, Colin Maclaurin Road, Edinburgh, EH9 3DW, UK
[b] James Watt School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK

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ABSTRACT

Seasonal thermal energy storage can provide flexibility to smart energy systems and are characterised by low cost per unit energy capacity and varying applicability to different geographical and geological locations. This paper identifies applications and reviews modelling approaches for seasonal thermal energy storage technologies in the context of their integration in smart energy systems. An example district-scale smart energy system is outlined to analyse three potential smart applications for seasonal thermal energy storage: (i) utilisation of multiple renewable energy sources, (ii) integrating waste heat and cool, and (iii) electrical network balancing. The rest of the paper focuses on modelling methods for borehole thermal energy storage and aquifer thermal energy storage in energy system analysis. Energy system tools for planning and detailed design stages are reviewed. Gaps are identified for planning tools in control strategies and open code. TRNSYS is found to be the dominant detailed design tool used to model large-scale borehole thermal energy storage. Co-simulation methods involving detailed physics and power system tools are also reviewed, including studies using co-simulation of a detailed physics tool to represent borehole or aquifer thermal energy storage alongside an energy system tool. A gap exists in co-simulation of borehole or aquifer thermal energy storage models with energy system tools capable of simulating both electricity and heat. In conclusion, seasonal thermal energy storage can provide flexibility through different smart applications at different scales, and modelling approaches using co-simulation methods offer a promising avenue for capturing potential benefits of these smart applications.

Abbreviations

4GDH - 4th Generation District Heating, 5GDHC - 5th Generation District Heating and Cooling, ATES - Aquifer Thermal Energy Storage, BHE - Borehole Heat Exchanger, BTES - Borehole Thermal Energy Storage, CFD - Computational Fluid Dynamics, CHP - Combined Heat and Power, DST - Duct Ground Heat Storage, PCM - Phase Change Materials, PV - Photovoltaics, PTES - Pit Thermal Energy Storage, RES - Renewable Energy Sources, SBM - Superposition Borehole Model, STES - Seasonal Thermal Energy Storage, THMC - Thermal, hydraulic, mechanical and chemical processes, TTES - Tank Thermal Energy Storage, UTES - Underground Thermal Energy Storage,

1. Introduction

Seasonal thermal energy storage (STES) can help manage the mismatch between supply and demand of renewable energy systems which can occur over seasonal and inter-annual periods. It has often been installed to increase the utilisation of solar technologies which produce useful energy with a high degree of seasonal variability; 51 out of 60 STES case studies examined by Yang et al. [1] have solar thermal as the main heat source. However, solar thermal is not the only heat source which can be used. This paper explores the ability of STES to enable synergies between energy sectors, identified from the smart energy system concept [2], to increase the utilisation of multiple energy sources such as stochastic renewable power generation and waste heat.

In the UK, there is an ongoing energy transition driving a growing installed capacity of wind power which is increasingly curtailed due to mismatch with demand or network constraints. Constraint payments to wind farms in the UK have risen between 2015 and 2021 from £90 to £140 million [3]. Additionally, there is a large potential of untapped

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*Corresponding author
andrew.lyden@ed.ac.uk (L. A.)
ORCID(s): 0000-0002-0986-8426 (L. A.)

waste heat from electricity generation sector, and the industrial and commercial sectors. The UK industrial sector alone is estimated to have a waste heat potential of 10-40 TWh/year [4]. It is possible that STES can provide value to the wider energy system by reducing the curtailment of wind power and taking advantage of untapped waste heat. These are examples of potential smart applications of STES pertinent to smart energy systems.

Smart energy systems are a well established concept which has been defined as: *"...an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system [5]."* STES technologies can enable these synergies between energy sectors and help contribute to an optimal overall energy system. A potential advantage of STES is their lower capital costs compared to electricity storage and domestic thermal storage [6] (up to 100x cheaper per kWh [7] for large-scale installations). The capital costs are sensitive to storage type, site availability, and land costs. In this paper smart applications are defined as combinations of supply, storage, demand, and control technologies which enable synergies between energy sectors.

Potential smart applications including STES need to be modelled to understand their performance and system benefits [8]. Energy system tools at the planning and detailed stage of design use a number of different approaches to modelling the different types of STES in energy systems [9]. However, these tools often do not contain all of the required functionality to accurately capture the dynamics of STES or they rely on exogenous inputs related to the interaction with the electricity sector. Detailed physics tools can capture the complex heat transfer mechanisms of STES, while power system tools can model the connected transmission and distribution electricity networks which can provide detailed inputs. Co-simulation methods, which couple two or more tools, can be used to model in detail the interaction between STES, heat, and electricity systems [10].

Previous papers have reviewed applications and modelling methods of different types of STES. Xu et al. [11] undertook a techno-economic literature review of the underlying physics, key characteristics, and case studies for sensible heat, latent heat, and chemical seasonal storage types. They identified the promise of combining STES with solar energy to replace fossil fuel dependence, but did not review modelling approaches for STES. Pinel et al. [12] reviewed available methods for STES in residential applications. They discussed methods for improving stratification and reducing losses, while analysing computational methods for simulating and optimising sensible heat storage systems. They did not discuss methods for modelling STES within energy system tools or co-simulation methods. The focus of the paper was on solar energy as the main heat source and not other sources of energy. Lanahan and Tabares-Velasco [13] provided a critical review of modelling and system design of Borehole Thermal Energy Storage (BTES) systems for higher system efficiency. Their work includes a useful review of energy system modelling tools for BTES, and discusses the gap of co-simulation with computational fluid dynamics (CFD) tools beyond the state-of-the-art approach of using parameter fit models. The paper does not review other types of STES or the integration of multiple energy sources. It also does not consider co-simulation with power system tools. Hesaraki et al. [14] focused on low temperature STES and their integration with heat pumps, and included a useful review on energy system tools and CFD tools. Their paper does not review the integration in smart energy systems, and does not discuss the use of co-simulation methods. Dahash et al. [15] reviewed the advances in STES for solar district heating applications. They provide a general review of all types of STES and the rest of the paper focuses on tank and pit thermal energy storage in terms of their construction, modelling (including co-simulation methods), performance indicators, and example projects. The main heat source discussed is solar, and the paper does not explore smart applications using multiple energy sources or co-simulation for aquifer thermal energy storage (ATES) and BTES.

This paper reviews the state-of-the-art of STES applications and modelling in the context of integration within smart energy systems. The aims are to: (i) set out potential smart applications for STES; and (ii) review modelling methods for integrating BTES and ATES into district-level smart energy systems. This paper is a valuable addition to existing literature because it reviews STES beyond the focus of only using solar energy and towards the use of multiple low-carbon energy sources from various sectors as informed by the smart energy system concept; and it reviews BTES and ATES modelling methods with energy system tools and co-simulation approaches (involving detailed physics tools and power system tools) which can support multi-sector and multi-vector analysis.

This paper is structured as follows: Section 2 provides an overview and describes a set of case studies of the different types of STES; Section 3 sets out a district-level smart energy system and identifies potential smart energy system applications of STES; Section 4 reviews energy system tools for planning and detailed stages of design of energy systems which integrate BTES and ATES; and Section 5 reviews and discusses the potential of co-simulation methods using detailed physics tools and power system modelling tools.

Table 1
Key characteristics of different types of STES (uses information from [11, 13, 14, 15]). Heat recovery efficiency is the percentage of the total heat injected to the STES later extracted over a year of operation.

	Tank Thermal Energy Storage (TTES)	**Pit Thermal Energy Storage (PTES)**	**Borehole Thermal Energy Storage (BTES)**	**Aquifer Thermal Energy Storage (ATES)**
Storage medium	Water	Water; Water mixture with gravel or sand	Ground saturated or unsaturated rock/soil	Ground material (sand/water/gravel)
Heat storage capacity	Water: 60-80 kWh/m3	Water: 60-80 kWh/m3, Gravel-water: 30-50 kWh/m3	15-30 kWh/m3	30-40 kWh/m3
Charging/Discharging (Heat flux)	High. Direct (pumping medium in/out); Indirect (heat exchanger)	High (Medium for gravel-water). Direct (pumping medium in/out); Indirect (heat exchanger)	Low with buffer required	Low/medium with buffer required
Operating temperature	<100°C, limited by insulation materials	Typically <80°C, limited by material of floating lid	40-90°C	Low temp: 13-25°C, Medium temp: 25-50°C, High temp: >50°C
Heat recovery efficiency	High (90-98%)	High/Medium (50-90%)	Medium (70-90%), no insulation on sides or bottom, dependent on year of operation	Medium (65-95%), no insulation
Depth below ground	<50m due to economic infeasbility [18]	5-15m	30-100m	Typical aquifer thickness - 20-50m, Typical aquifer depth - shallow (<30m) or deep (>30m)
Geological requirements	Stable ground, preferably no groundwater	Stable ground, preferably no groundwater	Drillable ground, favourable groundwater, high heat capacity, thermal conductivity	Requires natural aquifer layer, confining low-permeability layers, no or low groundwater flow, suitable water chemistry
Cost considerations	High CAPEX	Medium CAPEX	Low/Medium CAPEX, High drilling cost, low OPEX	Low CAPEX, Low drilling cost, high OPEX

2. Overview of Seasonal Thermal Energy Storage

There are four main types of STES with different characteristics which influence their ability to contribute to various smart applications as well as their suitability in different geographical and geological locations. The STES technologies categorised in this paper are Tank Thermal Energy Storage (TTES), Pit Thermal Energy Storage (PTES), Borehole Thermal Energy Storage (BTES), and Aquifer Thermal Energy Storage (ATES). BTES and ATES are types of underground thermal energy storage (UTES). Additional UTES types, including cavern and abandoned mine thermal energy storage, are not included in this review paper.

This section describes the different types of STES and discusses their key characteristics, which are provided in Table 1. Table 2 consists of a set of case studies which have been picked as they are representative of a range of STES types and highlight the gap in the use of STES in conjunction with multiple energy sources. Several studies have been undertaken which gather and analyse real-world case studies of STES, and these should be referred to for further information [1, 16, 11, 17].

Tank Thermal Energy Storage (TTES) stores sensible heat in a medium, such as water, within a tank structure which is well insulated to minimise heat losses [30]. These are common in domestic applications in the form of hot water cylinders, buffer tanks, and thermal stores which are used to store hot water for use in space heating and domestic hot water provision [31]. Additionally, the storage medium is most commonly water but heat transfer oils and molten salts have been used [32]. Large-scale TTES systems have been installed either above ground or, partly or fully, underground. Despite higher installation costs for underground constructions these benefit from lower heat losses and reduced above-ground land footprint [30]. TTES have high charge and discharging rates as they store heat energy in water limited only by pumps and pipe sizes (or heat exchangers if used) [33]. They can typically store more efficiently than other types of STES because of the high level of insulation around the tank. However, the costs of installation are typically higher due to this.

Pit Thermal Energy Storage (PTES) consists of a ground excavated site filled with a storage medium, covered by a floating lid and optionally insulated on the sides [15]. The storage medium is typically water, but mixtures of water and gravel or sand have also been used to reduce costs. PTES typically have lower costs than TTES because they use less insulation materials (often only the top is insulated) [15] and often utilise existing excavated sites. There is a growing number of PTES being installed in Denmark alongside solar collectors [34]. They have high charge and discharge rates, which potentially enables the flexible operation of heat pumps to respond to price signals and provide grid services [35].

Borehole Thermal Energy Storage (BTES) requires drilling of vertical or horizontal boreholes and insertion of pipes into the ground in order to store heat using rock and soil as the storage medium [36]. A heat transfer fluid,

Table 2
Selection of real world case studies of different types of STES

Case Study, (year installed)	Connected buildings	Primary heat source	STES type	STES detail	STES volume	References
Drake Landing Solar Community, Canada, (2007)	52 detached buildings	Roof-mounted flat plate solar collectors, 2293 m^2	BTES	144 boreholes, 35 m deep, 24 parallel, 6 series, (sand siltey, clayey), top of borehole 30-75°C	34,000 m^3 (ground estimated)	[19]
Dronninglund, Denmark, (2014)	Town, 1350 customers	Ground solar collectors (37,573 m^2, 26 MWth), absorption heat pumps (4.7 MW), bio oil boiler (5 MW)	PTES	Water medium, floating lid, abandoned gravel pit, polymer liners, 20-85°C at top	60,000 m^3	[20]
Brædstrup, Denmark, (2007)	Town, 1482 customers	Ground solar collectors (18,600 m^2), electrical heat pump (1.3 MWth), 10 MW electrical boiler, natural gas CHP	BTES	48 boreholes, 3 m distance, 45 m depth, 16 parallel, 6 series, mussell shells used for top insulation, (clay/till), centre of BTES 17-50°C	19,000 m^3	[20]
Marstal, Denmark, (2012)	2200 customers	Ground solar collectors (15,000 m^2), electrical heat pump (1.5 MWth), 4 MW biomass boiler with 750 kW organic rankine cycle unit, bio oil boilers	PTES	2x pit storage tanks, 30-95°C at top	75,000+ 10,000 m^3	[20]
Vojens, Denmark, (2015)	2000 customers	Solar collectors 71,000 m^2	PTES	Excavated old sand pit, separated by heat exchanger, max design temperature 90°C	203,000 m^3	[21]
Munich, Germany, (2007)	300 apartments	Roof mounted flat plate collectors (2,900 m^2), 1.4 MW absorption heat pump	TTES	Water medium, buried tank	5,700 m^3	[22]
Eggenstein, Germany, (2007)	12,000 m^2 floor area of buildings	1,600 m^2 flat plate collectors	PTES	Gravel/water medium, max design temperature 80°C	4,500m^3	[23]
Crailsheim, Germany, (2007)	260 apartments, school, gym	7300 m^2 flat plate collectors, 530 kW electric heat pump	BTES	80 boreholes at 55 m depth, (mudstone, limestone), 3-90°C for both high and low temperature heat pumps	37,500 m^3	[24]
Rostock, Germany, (2000)	108 flats	Roof-mounted flat plate solar collectors, 980 m^2, 110 kWth electric heat pump for discharging STES	ATES	2 wells, bottom of aquifer 30 m below surface, temperature limited to 50°C to prevent changes to ground water chemistry	20,000 m^3	[25]
Eindhoven, Netherlands, (2001)	University campus	Heat and cooling balancing across seasons, heat pumps for 17 MWt for heating or cooling	ATES	16 cold wells, 16 warm wells 28 m top aquifer-80 m bottom aquifer depths	1500 m of total field piping	[26]
Chifeng, China, (2013)	Large-scale district heating network	75 MW waste heat sources, 169 m^2 solar thermal	BTES	468 boreholes at 80 m depth	500,000 m^3	[27]
Pimlico, UK, (1950)	3,256 homes, 50 business premises and three schools	2x 1.55 MW CHP and 3x 8 MW gas boilers	TTES	Water medium, above ground	2,300 m^3	[28]
Beaufort Court, UK, 2005	Head office and visiting centre for the RES group	Hybrid PVT array	PTES	Floating insulated lid, pre heats air supplied to offices	1,500 m^3	[29]

water or similar refrigerant, is circulated through the borehole pipes in a closed loop to inject or retrieve heat from the ground. Pipes are commonly single and double U-tubes [37], and depending on subsurface conditions the boreholes are grouted to stabilise them and improve thermal contact between the ground and pipes [37]. The performance of the system is dependent on the subsurface conditions and existence of ground water, and a large proportion of the costs are from drilling the boreholes. A BTES system can be installed in a wider variety of geological conditions, in contrast to the specific requirements of ATES. Reported efficiencies of BTES are lower than TTES and PTES, but they have lower surface area requirements. BTES has low charge and discharge rates, meaning that system operation may be improved by also using short term storage systems, such as surface TTES or phase change materials (PCM) [19]. BTES have lower maintenance requirements compared to ATES. BTES can be coupled with a heat pump to boost water temperatures as they store heat at low temperatures. High thermal conductivity is good for extraction and storing heat, however, can lead to poor recovery factors due to greater thermal propagation away from the heat exchanger during storage [38].

Aquifer Thermal Energy Storage (ATES) uses wells to inject and extract water to and from aquifers, which are naturally occurring underground reservoirs of groundwater [39]. Typically, for open loop systems, two separate wells are drilled, one cold and one warm. During charge, water is extracted from the cold well, heated by the heat source, and then injected into the warm well. This operation can also be used to provide cooling. The flow is reversed during discharge, where water is extracted from the hot well, cooled in a heat exchanger or heat pump, and then injected into the cold well. While ATES can provide heating and cooling using both wells, it can also provide heating or cooling only. ATES has advantages because it utilises the high specific heat of water and the natural underground formations as storage mediums which decrease excavation requirements [39].

All of the outlined STES types are characterised by low costs (relative to other storage technologies such as electrical batteries), but vary in charging/discharging rates, operating temperatures, heat recovery efficiencies, and geological requirements. TTES and PTES offer high heat capacity, high charging/discharging rates, high operating temperatures, and high heat recovery efficiencies and they are expected to be installed widely alongside solar collectors where there is sufficient land availability and suitable geological conditions, as can be seen in the uptake of PTES in towns around Denmark. However, BTES and ATES offer the lowest installation costs (with ATES having lower drilling costs than BTES, dependent on the depth of drilling), and while ATES requires a natural aquifer layer, BTES can be installed in a wider range of locations with a lower land footprint than both TTES and PTES. Provided there is an abundance of low-cost energy to mitigate low heat recovery efficiencies, BTES and ATES are very promising storage technologies. They can be applied in smart energy systems in order to take advantage of excess renewable electricity production and waste heat. BTES and ATES are the focus of this paper when reviewing modelling approaches.

3. Smart Energy Systems and Seasonal Thermal Energy Storage

Smart energy systems consider all sectors to identify synergies which help deliver system benefits. 4th Generation District Heating (4GDH) is a concept describing smart thermal grids which form a pivotal component of smart energy systems [40]. 4GDH is characterised by lower operating temperatures (<50-60°C), low energy demands, bidirectional flows, and cross-sector integration. It is recognised that the feasibility of district heating varies in different locations and countries, with lower heat distribution costs in dense urban areas with concentrated heat demands [41]. STES can play an important role in 4GDH [42, 43] as it can enable synergies between sectors. The synergistic benefits enabled by STES are referred to as smart applications in this paper. While STES can be used with previous generation district heating systems, this section focusses on 4GDH where integration with other sectors is a key aspect. The 5th Generation District Heating and Cooling (5GDHC) concept [44] is considered parallel to the 4GDH concept [45]. 5GDHC are decentralized, bi-directional, close to ground temperature networks that utilise warm and cold return flows and thermal storage. Therefore, for the purposes of this review, 5GDHC is included in the smart energy systems concept.

This section starts by setting out an example of a district-scale smart energy system including the energy technologies, sectors, and vectors in which STES may operate within. This context is used to explore potential smart applications of STES.

3.1. District-level Smart Energy System

A district-scale smart energy system includes a wide variety of energy vectors, sectors, and technologies and an example is shown in Figure 1. This example energy system does not constitute an exhaustive list of all potential components but is intended to capture the potential synergies in which STES can participate. It is intended to be representative of a future, net zero carbon emission energy system, and there may still be emissions which impact air quality, such as from the combustion of hydrogen.

Four energy vectors are included: local electricity distribution network, heating network, cooling network, and local hydrogen pipe network. Four categories of component are included across these energy vectors: demand, storage, conversion, and energy system integration. Demand components take energy from their vector; storage components store energy and charge/discharge to/from their energy vector; conversion components take energy from energy vectors or resources and convert the energy to supply a different energy vector; and energy system integration components represent the interaction between the district-scale energy system and the wider energy system.

The local electricity distribution network is the section of the electricity network which is defined by the boundaries of the district-scale energy system. This network is where electricity demands are met; electricity storage technologies are charged and discharged; energy conversion technologies feed the electricity they generate; and where the wider energy system is integrated via the connection and market mechanisms such as grid services and tariffs.

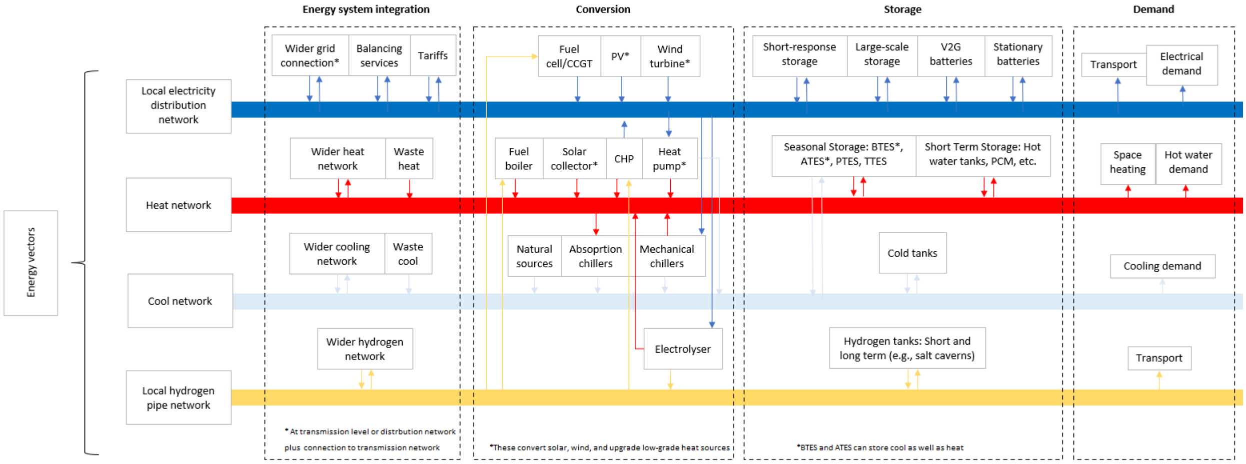

Figure 1: Whole energy system schematic. Bidirectional travel is possible between the various components and energy vectors.

The heating network transports heat around the energy system and this can be via flow and return hot water pipes, while a number of different configurations and flow and return temperatures for heat networks exist [46]. STES may directly connect to a heat pump or solar collector, but the smart energy system schematic only shows a simplified representation. The smart energy system schematic also shows that phase change materials (PCM) and hot water tanks can be installed alongside STES to offer short and medium length storage of heat. PCM in district heating has been investigated in simulation studies [47]. Fuel boilers can take from a fuel vector (hydrogen in this case) to generate heat; solar collectors use solar energy to generate heat; CHP can take from a fuel vector to generate both heat and electricity; and heat pumps can use low-grade heat sources along with electricity (which can be from renewable sources) to generate heat. There is potential for integrating a local heat network with a wider heat network and to utilise external sources of waste heat.

The cooling network transports cooling energy around the energy system in a similar fashion to the heat network. Typically, a dual pipe system is used with a forward flow of cold water being delivered, to meet cooling demands, alongside a return flow of used water to the cool production units. Natural sources (e.g. rivers, seawater), absorption chillers (use heat), and mechanical chillers (use electricity) can generate the cool and couple to other energy vectors. Cold tanks can provide flexibility, and the cool network can be integrated into the wider energy system with the use of waste cool and connection to a wider cooling network.

Numerous synthetic fuels can be utilised as an additional energy vector which acts in a similar manner to the widely adopted natural gas network. In this schematic hydrogen has been adopted as it has been identified in many studies as a vital energy vector for reaching net zero carbon dioxide emissions [48]. A hydrogen network has been used in Figure 1 instead of a fossil fuel energy vector, such as natural gas, in order to illustrate a net zero carbon emission system without significant carbon abatement technologies. Additionally, electrofuel production such as Power-to-Liquids and Power-to-Chemicals are not included in Figure 1 but are likely to play a pivotal role in future smart energy systems [49].

3.2. Smart Applications of Seasonal Thermal Energy Storage

This section explores the potential smart applications of STES. Using the example district-level smart energy system described in the previous section, three smart applications of STES are identified: utilisation of excess renewable energy sources; integration of waste heat and cool; and provision of electrical network balancing.

3.2.1. Utilisation of Renewable Energy Sources

The utilisation of renewable energy sources (RES) can be increased by coupling of the electricity and heat sectors through conversion technologies, such as heat pumps, electric boilers and CHP, in addition to thermal storages, such as STES and short term thermal energy storage. Figure 2 displays the various components which can contribute to the energy flows which enable STES to increase the utilisation of RES. This section discusses power-to-heat technologies and STES in their ability to increase the utilisation of RES which are connected locally (e.g., photovoltaics (PV) and wind turbines) or through a wider grid connection. Included in the figure are fuel cells which may use synthetic fuels generated from RES [50] and electrical storages which may have been charged using electricity generated from RES [51].

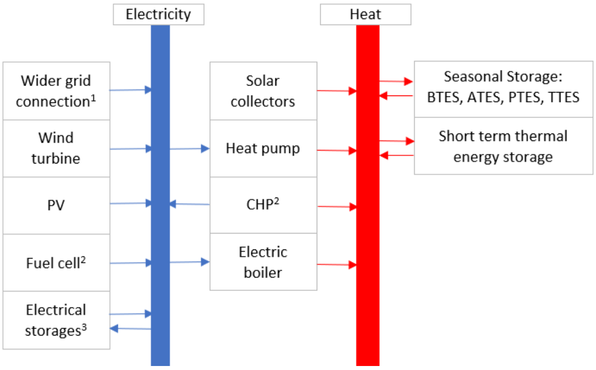

Figure 2: Utilisation of RES. Key: 1 - Wider grid connection with electricity from RES, 2 - Using synthetic fuel generated from RES, 3 - Electrical storages which have been charged with electricity from RES

The majority of STES installations to date have been alongside solar collectors [1], in order to increase the utilisation of the heat produced in the summer to meet the larger space heating demands in the winter. It has been established that STES can increase the utilisation of solar collectors [52]. For example, an optimisation study [53] showed that achieving 100% renewable heating for a residential district is possible for a large cost with significant STES capacity, but they recommended a more reasonable aim of 60-80% heating from solar energy.

As electrical power systems become increasingly reliant on variable renewable power sources, there will be an increase in cheap, or excess power available which would otherwise be curtailed [54]. STES have large capacities which can offer the large flexibility required to increase the utilisation of excess power generation. However, the seasonal cost difference would have to be large to make use of this in seasonal storage. Power-to-heat technologies, such as heat pumps and electrical boilers, can convert excess power generation to heat which can be stored as STES. Power-to-heat technologies and curtailment of wind have been identified as the most cost-effective flexibility option for the Finnish energy system [55]. Another modelling study demonstrated power-to-heat as capable of improving the flexibility of CHP systems [56]. Both studies incorporated thermal energy storage without exploring the application of STES. Studies of district heating systems incorporating PV panels or wind turbines have shown that including power-to-heat technologies can increase utilisation of excess power. A study modelling district heating integrated with PV panels found that heat pumps converted 47% of excess PV generation to heat [57]. Another study found that 10-40% of excess wind generation from a local wind farm could be utilised within a connected district heating network [58].

While adoption of small-scale PV installations is becoming widespread, future renewable power production will be a mix of both centralised and distributed installations [59]. Centralised, large-scale installations should be considered in regards to their connection to district-level smart energy systems via a wider grid connection. Therefore, there is opportunity for power-to-heat technologies with STES to increase utilisation of RES produced on the wider energy system. Thermal storage was shown to be able to reduce curtailment in scenarios for the Irish energy system [60]. Holmér et al. [61] demonstrated the ability of thermal energy storage to adapt to variable production on the power system, and promoted PTES and TTES over BTES and ATES due to the higher charging/discharging rates possible. However, this conclusion did not account for the value of low installation cost and low above-ground land use associated with BTES and ATES.

3.2.2. Waste Heat and Cool

Waste heat and cooling from industry and commercial sectors, as well as electrical power production, can be underutilised in part due to geographical and temporal mismatch to heat demands. However, thermal energy storage can solve this by decoupling supply and demand [62], and STES has been installed in order to increase utilisation of waste heat [63]. Additionally, waste heat released to the atmosphere has been shown to have similar immediate radiative forcing effects as by CO_2 emitted, contributing to climate change [64].

Figure 3 illustrates the technologies which can contribute to this smart application. There exists significant waste heat in the UK; Papapetrou et al. [65] calculated a waste heat contribution of 24 TWh/year across all industries in the UK. Waste heat technologies can be applicable in recovering heat from commercial and industrial sectors [66], while mechanical [67] and absorption [68] heat pumps can upgrade low-grade sources. There are a growing number of case studies emerging which utilise waste heat, see [69] for a compilation of these. Waste heat can also be used to meet cooling demands, e.g, through a waste heat driven adsorption cooling cycle [70].

Studies have modelled STES specifically for integration with waste heat. Guo and Yang [71] modelled a large BTES system with connection to both industrial waste heat and solar energy sources, using TRNSYS, and showed that BTES improved the flexibility of the energy system. McDaniel and Kosanovic [72] modelled BTES coupled with a CHP, also using TRNSYS, and showed that BTES is economically and environmentally promising because it allows greater flexibility in the operation of the CHP. Hirvonen and Kosonen [73] modelled a BTES supplied by energy from waste incineration, again using TRNSYS, and waste heat was able to meet 37-89% of annual heat demand.

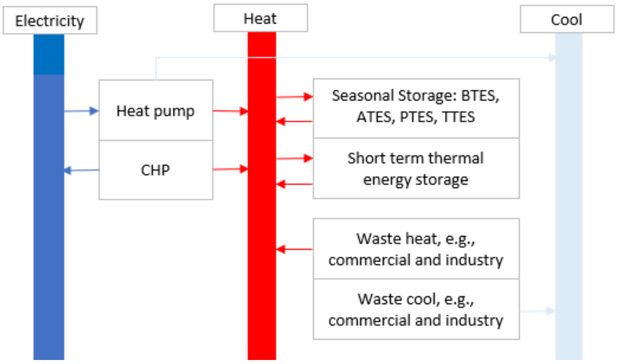

Figure 3: Waste Heat and Cool

3.2.3. *Electrical Network Balancing*

Electrical heat production units, such as heat pumps and CHP, can be operated flexibly by integration with STES to provide distribution and transmission electrical network services. This can be performed directly by participation in explicit balancing services markets such as frequency response [74], by responding to demand and supply matching via a wider grid connection [75], and operating depending on emerging time-of-use tariffs from electricity suppliers [76]. Although BTES and ATES are characterised by low charging/discharging rates, they can still increase the flexibility of connected technologies which can respond fast enough in order to aid electrical network balancing. Figure 4 illustrates the technologies which can play a role in STES enhancing the ability of a system to provide electrical network balancing.

Heat pumps have been shown to be able to provide intra-day balancing [77], and large-scale heat pumps have been shown to be able to provide frequency support with limited impact on meeting the heat demand [78]. Additionally, CHP has been modelled to showcase the benefits of operating them to provide frequency response [79, 80].

Short-term thermal energy storage which can charge/discharge quickly may be used directly to store heat from heat pumps or CHP when providing flexibility to the electricity network. These can then be connected to the STES which provides the short-term storage with greater flexibility as the STES can act as an additional heat sink/source, to enhance the use of the short-term storage capacity. In addition, power-to-heat-to-power storage technologies are advancing [81].

The ability of STES to increase system flexibility to contribute to electrical network balancing has received little attention in literature, and generally it is the broader category of thermal energy storage which has been discussed in relation to electrical network balancing [82]. This is likely due to the low charging/discharging rates. However, given the low installation costs there is potential for STES to enable other technologies to operate more flexibly and to aid electrical network balancing.

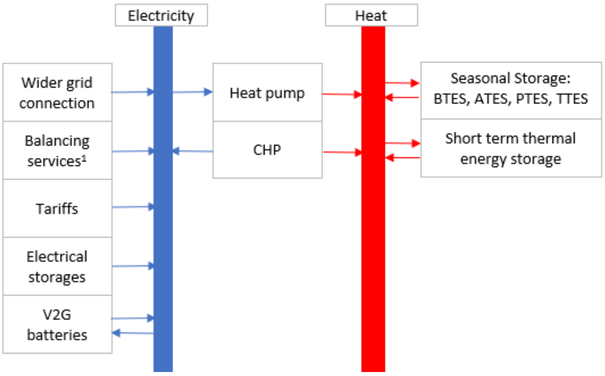

Figure 4: Electrical Network Balancing

4. Energy System Modelling Tools

STES needs to be modelled in order to quantify and understand its performance. This is particularly important when integrating STES into smart energy systems, as outlined in the previous section, as this introduces complex interactions between energy sectors and vectors. This section reviews existing energy system modelling tools which have been categorised into planning and detailed design tools. The focus of the following modelling review sections are on BTES and ATES.

Energy system modelling tools were identified primarily through modelling tool review papers [13, 14], and supplemented by literature surveys of STES modelling studies found through searches in online databases (e.g., using search engines like Google Scholar and Web of Science with keywords such as "seasonal thermal energy storage" and "long term thermal energy storage"), and existing databases of energy system tools (Open Energy Modelling Initiative Wiki [83] and EnergyPLAN Other Tools database [84]). The tools identified in Section 4 and 5 will likely not represent all available tools, but aims to capture the most widely used and review their capabilities.

4.1. Planning/Feasibility/Pre-design Energy System Tools

Planning energy system modelling tools are used to inform feasibility studies and explore concept designs. They often use simplified model representations, or pre-simulated results from detailed design studies, to simulate the components of proposed energy system designs as available data is often limited and fast computational speed is desirable at this stage of the design process.

There are planning modelling tools which have the capability to model STES, and a review is contained in Table 3. The tools reviewed have been identified from relevant review papers [13, 14]: EnergyPLAN, MINSUN, SOLARTHERMIE-2000, and SOLCHIPS. There are also a number of tools which have been disseminated as part of the SDH (Solar District Heating) project [85]: Fjernsol II, SDH Online Calculation Tool, and SUNSTORE-4 Feasibility Evaluation Tool. These types of tools typically only consider thermal energy flows.

There are a number of limitations of the identified tools. EnergyPLAN lacks a detailed seasonal thermal storage model in addition to the necessary flexibility to incorporate a suitable control strategy. However, it is highly suited to modelling the smart energy systems. MINSUN, and Fjernsol II are either not available (access to these tools could not be found) or not in English. SOLCHIPS has promising functionality in modelling the solar collector, load, and STES, however, it has not been accessible and does not include smart energy system integration with components such as on-site PV, grid connection, or other types of storage such as battery storage. The SDH Online Calculation Tool and the SUNSTORE-4 Feasibility Evaluation Tool are tools capable of assessing the technical and economic feasibility of a limited range of configurations of energy systems with solar collector and STES. However, because they rely on pre-simulated results from TRNSYS models, they lack flexibility in location and choice of energy system components (only results for pre-configured systems can be obtained).

There is scope for an existing planning-level tool (such as PyLESA [91]) to be extended to include a sufficiently detailed STES model and suitable control strategy to address these limitations. The extended tool should be able to quickly assess a wide range of energy system configurations, including STES. This functionality is required for investigating, at the planning-stage, the integration of STES into smart energy systems which cover a range of energy

Table 3
Review of STES modelling capability in planning energy system modelling tools. "Not available" indicates that this information could not be found.

Tool	Description	Timestep	STES Model	Reference
EnergyPLAN	Multi-sector national energy system modelling tool	Hourly	Simple energy model	[45]
MINSUN	Pre-design simulation and optimization modelling tool based on TRNSYS	Not available	Not available	[86, 14]
SOLARTHERMIE-2000	Recommendations for dimensioning parameters of solar collectors and storage	Not available	Not available	[87]
SOLCHIPS	Pre-design and optimisation tool for solar heating systems with STES	Not available	Energy and mass balance with temperature dependence but no energy system integration	[88, 89]
Fjernsol II	Tool to compare price of the solar heat with alternative heat sources	Monthly	No	[85]
SDH Online Calculation Tool	Pre-design with results based on more than 100,000 TRNSYS simulations for solar district heating with TTES	Hourly (outputs from TRNSYS)	TRNSYS STES model	[90]
SUNSTORE-4 Feasibility Evaluation Tool	Sizing and feasibility evaluations of 5 different hybrid system concepts, including large scale solar heating system, seasonal or short term energy storage, biomass boiler system, heat pump and ORC for electricity	Hourly (outputs from TRNSYS)	TRNSYS STES model	[85]

vectors and sectors. Two simplified energy flow methods for simulating STES in hourly timesteps have been identified in literature which could be incorporated with an existing planning-level modelling tool [92, 93].

4.2. Detailed Energy System Modelling Tools

Detailed energy system modelling tools are used to provide accurate understanding of performance, as well as sufficient detail in order to size various components. Detailed energy system modelling tools capture the transient and dynamic physics of energy systems. They have often been used to simulate individual buildings, and have also been utilised to simulate district/community/local scale energy systems such as the generation, storage, and distribution elements of district heating networks. These components are important in modelling smart energy systems. These tools, and more, have been reviewed and compared; Crawley et al. [94] compared the features and capabilities of twenty major building energy simulation programs, and Harish and Kumar [95] presented a very detailed review of all the significant modelling methodologies which have been developed and adopted to model the energy systems of buildings.

There are a number of detailed modelling tools which have been identified in review papers [13, 96] as having capability in modelling STES: HVACSIM+, eQuest, Geostar, EnergyPlus, and TRNSYS. Often these tools have incorporated ground heat exchanger models to simulate ground source heat pumps, but these models can have application to borehole thermal energy storage systems. See Table 4 for details on BTES modelling capabilities of these tools.

HVACSIM+, eQuest, and EnergyPlus, use pre-computed response functions solved for specific ground heat exchanger geometries. The methods used all have a common origin and are based on extensions to Eskilson's ground

Table 4
Detailed modelling tools for BTES

Tool	Description	BTES Model	Example study	Reference
HVACSIM+	Computer simulation tool to simulate entire building systems	Hybrid ground source heat pump system using extended Eskilson's g-functions	[96] cites [97] as simulating BTES but no injection of heat mentioned	[98]
eQuest	Uses the DOE-2 simulation engine to quickly simulate building energy performance	Can model horizontal or vertical ground loop heat exchangers using extended Eskilson's g-functions	Not found	[99]
EnergyPlus	Open-source whole-building energy modeling (BEM) engine	A vertical borehole ground-loop heat exchanger model which uses extended Eskilson's "g-functions" to model response to time-varying heat fluxes	Outputs compared to an analytical line source approximation and found to be within 2°C [100]	[101]
Geostar	Design and simulation of vertical GHEs	Model ground heat exchangers according to a set of design conditions including: the building load, ground thermal properties, borehole configuration, and heat pump operating characteristics	Coupled with analytical heat transfer models for the vertical ground heat exchangers [102]	[103]
IDEAS	Modelica library allowing simultaneous transient simulation of thermal and electrical systems	Hybrid borefield model which combines a short-term model and a long-term model to obtain g-functions	Used to improve or optimize HVAC systems of buildings [104]	[105]
TRNSYS	Software environment used to simulate the behavior of transient systems	Two analytical models: (i) Duct Storage Model considers the convective heat transfer in the pipe in a borehole and the conductive heat transfer in the ground, (ii) Superposition Borehole Model calculates the three-dimensional temperature field in the ground	See Table 5	[106]

heat exchanger model [107]. The response functions are known as g-functions, and are computed based on spatial superposition of a two-dimensional (radial-axial) simulation of a single borehole. However, these response functions are not usually suited to energy system models as they have limited accuracy at short timesteps and are usually pre-computed for timesteps from days to very long periods such as hundreds of years. HVACSIM+, eQuest, and EnergyPlus extend Eskilson's g-functions to time steps of an hour or sub-hourly by computing the response for a single borehole to a pulse.

TRNSYS is the most widely applied energy system modelling tool to studies which include seasonal thermal storage, in particular BTES. The popularity is due to the strengths of the tool in modelling solar systems and the availability of the Duct Ground Heat Storage (DST) model [108] which is used to model borehole thermal energy storage. A number of TRNSYS studies analysing BTES and ATES have been identified in literature and are described in Table 5.

The DST model (Type 557, before TESSLibs18, change to Type 548 after TESSLibs18 release) considers the convective heat transfer in the ducts (pipe in a borehole) and the conductive heat transfer in the ground [108]. It treats the problem as a superposition of a global problem, which accounts for the flows between the store and the ground, and a local problem, which accounts for the heat transfer between the heat carrier fluid and the store. The local problem is split into (i) local solutions around the borehole and, (ii) steady-state flux part which reduces the number of local solutions (and decreases computational time). The global problem and the local solutions part of the local problem

Table 5
Description and details of selected TRNSYS studies including BTES and ATES

Reference	Description	Location	Heat demand	Heat sources	STES details	Results
Guo and Yang [71]	Long-term simulation and sensitivity analysis of real-world large-scale BTES	China	Large-scale urban district heating network	Multiple waste heat (total 75 MW) and 169 m^2 solar thermal	BTES Type 557: 468 boreholes with volume up to 500,000 m^3	TRNSYS provides reliable predictions of performance when calibrated using real data, and is useful for system design and optimisation.
Rosato et al. [109]	A parametric analysis to investigate the dependence of the performance of the system on BTES characteristics	Italy	6 residential buildings and 3 schools	39x 2.51 m^2 of solar collectors	BTES Type 557: volume up to 352 m^3	Proposed system reduces primary energy usage; soil and grout thermal conductivity influence performance; spacing of the U-pipe and heat carrier fluid do not influence performance.
Maximov et al. [110]	Optimised a solar district heating network with a fully parametrised model linked to a multi-objective optimisation tool	Chile	18 residenial buildings totalling 144 flats	Solar collectors and auxiliary gas boiler sized in optimisation	BTES Type 557: sized in optimisation	BTES has the potential to decrease emissions by around 90% while increasing levelised cost of energy by less than 20% compared to conventional alternatives.
Renaldi and Friedrich [111]	A techno-economic analysis of a solar district heating system with seasonal thermal storage in the UK	UK	Space heating demand of 52 energy efficient homes	2293 m^2 of solar collectors	BTES Type 557: 144 boreholes of 35 m depth	Increasing solar collector and BTES size, and soil properties, have significant techno-economic influence, while increasing borehole number had a greater influence than increasing borehole depth. Economic incentives or policy support are required for competitiveness
Zeghici et al. [112]	Energy performance of changing heating source for an old and inefficient district heating system	Romania	13 multi-storey buildings and a kindergarten	Heat pump and CHP	ATES from author's previous work: depths below ground surface from 900 to 2300 m, temperature between 35 °C and 45 °C	The results show improved energy efficiency with reductions in primary energy consumption of 44% when compared to the existing old district heating system, and a decrease in CO_2 emissions of 82%.

are solved by explicit finite difference method (solving differential equations by approximating derivatives with finite differences), while the steady-state flux part is solved by an analytical solution (gives exact solution). The temperature is then calculated using superposition methods.

Another BTES model has been developed to work with the TRNSYS tool, the Superposition Borehole Model (SBM), TRNSYS Type 281 (non-standard type which requires manual install [113]). The SBM calculates the three-dimensional temperature field in the ground and can work with any number of vertical boreholes. The heat conduction in the ground is solved by explicit finite difference method. To reduce the computational time, the steep temperature gradients very close to the boreholes are solved by superposition technique. Using the finite difference method would require a very fine mesh to accurately capture the thermal propagation in proximity to the borehole. The convective heat flow within the pipes in the borehole is balanced against the conductive heat flow between the pipe and the borehole wall. The heat balance equations in the borehole are solved assuming steady state.

The BTES models used in EnergyPlus, TRNSYS (DST model), and HVACSIM+ were compared to measurement data to investigate their accuracy [114]. This study showed EnergyPlus, TRNSYS, and HVACSIM+ under-predicted measurement by a maximum of 6%, 11%, and 24% respectively in the peak heating months of December through February.

Modelling of ATES using detailed energy system tools has been predominantly undertaken using TRNSYS [115, 116, 117, 118]. A two-well model of ATES called TRANSAT (Type 345) has been incorporated into TRNSYS which assumes that the two wells are not thermally connected [119], and studies have been undertaken using this model [120, 121, 122]. However, TRANSAT has become unavailable. There is limited modelling of ATES in energy system tools, but there are approaches which use co-simulation to model ATES as discussed in the next section.

5. Co-simulation Methods

In this section the potential for co-simulation of energy system modelling tools with both detailed physics tools and power system modelling tools is explored. Detailed physics tools have been applied to model BTES (e.g., using ANSYS [123, 124]) and ATES (e.g., using COMSOL [120]), and typically offer a more accurate approach to predicting performance than models used in energy system tools. Electrical power system modelling tools are used to simulate and optimise power flow of transmission and distribution networks, and offer a method for analysing the role of district-level smart energy systems in the context of the wider energy system.

Co-simulation methods integrate two, or more, tools at a time and have several advantages including reuse of state of the art tools, promoting collaborative design and development, and quicker development of advanced modelling capabilities to analyse novel systems [125]. Co-simulation methods are used to bridge the gap between modelling tools in the cases where the individual modelling tools do not possess sufficient capability to simulate cross-sectoral systems which are vital in the smart energy systems concept. This is particularly the case with highly detailed and single domain tools.

There are ongoing efforts on creating integrated modelling environments which have the capability to co-simulate models at different temporal and spatial resolutions for different energy sectors at the urban/district energy systems scale [126]. Runtime infrastructure is required to facilitate the temporal transfer of data between tools, and these have been reviewed for the urban/district scale [127] (e.g., Functional Mockup Interface to co-simulate Modelica tools [128], Harmonizer which has been used to co-simulate TRNSYS and ESP-r [129], and Building Controls Virtual Test Bed (BCVTB) to co-simulate a building in EnergyPlus and the HVAC and control system in Modelica [130]).

5.1. Detailed Physics Tools

A key challenge and opportunity remains due to limited linkage and coupling between detailed physics tools which model STES in the subsurface and energy system tools which model the rest of the energy system, typically above the surface. BTES and ATES can be modelled as (1) a detailed physics model looking at subsurface heat transfer of the geothermal system, such as the aquifer and/or borehole and the surrounding soil (detailed physics tools); (2) a full dynamic system including multiple energy sectors and vectors, e.g., heating, electricity (energy system tools); or (3) a combination of whole-system dynamic model and a detailed physics subsurface model (co-simulation).

A detailed physics tool solves a series of governing equations, either analytically or numerically, coupling thermal, hydraulic, mechanical and/or chemical (THMC) processes that occur in the subsurface. Several detailed physics tools have been used to model the subsurface, either in conventional extraction studies or in STES-focused studies. These tools include but are not limited to: OpenGeoSys ([131]), SHEMAT ([132]), FEFLOW ([133, 134, 135]), MATLAB ([136]), MODFLOW ([137, 138, 139]), COMSOL ([140]), and TOUGH2 ([141]) (highlighted in table 6). OpenGeoSys is a THMC solver that has been used to model extraction in closed and open systems ([142, 143, 144]). FEFLOW is a coupled Thermal-Hydraulic-Chemical (THC) solver which has been used to evaluate heat extraction and thermal energy storage for shallow and deep intervals, using single to multi-well configurations ([145, 146, 147, 148]); it also has the potential to model mechanical processes through plug-ins [149, 150]. MATLAB has been used to develop code using a variety of spatial discretisation methods that solve both heat and fluid flux (coupled thermal-hydraulic (TH) processes) in closed-loop BHEs ([151, 152, 153, 154, 155, 156]) and open-loop aquifer systems ([155]), while COMSOL (THMC solver) and TOUGH2 (TH solver) have been used for thermal storage and extraction ([157, 158, 159, 160]). While several works have built in-house codes based on MATLAB for simulating closed-loop BHEs, the open-loop system in [155], used the MATLAB Reservoir Simulation Toolbox (MRST) [161]. It is also worth noting that MRST is capable of simulating THMC physics.

Although some tools have been used in the past with a stronger focus on extraction, they all have the capability to model underground thermal energy storage (UTES). Typically, detailed subsurface physics tools use numerical methods (finite-element, finite-volume or finite-difference), or a semi-analytical approach. This allows more detailed and accurate representation of the subsurface in comparison to analytical methods which rely on simplifications. While it is common to use the finite-difference method for the temporal discretisation, spatial discretisation is often performed using different methods; with literature largely focused on finite-element and finite-volume methods due to their greater flexibility in meshing subsurface geometry.

5.1.1. Borehole Thermal Energy Storage (BTES)

Tools that investigate detailed subsurface physics of BTES including the borehole heat exchanger (BHE) and heat transfer in the surrounding subsurface include analytical-based software such as GLHEPRO [165] and Earth Energy Designer (EED) [166]. However, these are limited to a pre-defined geometry and geological strata are not considered. To allow for more flexibility, a hybrid semi-analytical solution can be used, including an analytical model for the BHE and a numerical model for the surrounding formation. This has been implemented in BASIMO, a MATLAB-based code for optimization of BHE arrays [167, 153]; however, a major limitation of this is that groundwater flow (and, therefore, advective heat transport) is not incorporated. It is worth noting that further incorporation of governing equations for advective heat transport in the subsurface could be programmed in further work.

Table 6
Tabulated software comparison (modified and simplified from [127]). FDM=finite difference method, FEM=finite element method, FVM=finite volume method, T=thermal, H=hydraulic, M=mechanical, C=chemical. All software are capable of simulating both ATES and BTES. *MRST is an open-source code, rather than simulator, that supports THMC physics and different methods of discretisation.

Software	Discretisation	Processes	Reference
Ansys Fluent	FVM	THM	[162]
COMSOL	FEM	THMC	[157]
FEFLOW	FEM	THC	[135]
MATLAB Reservoir Simulation Toolbox (MRST)	FEM, FDM, FVM	THMC*	[155, 161]
BHE MATLAB Tools	FEM, FDM, FVM	TH	[153] (FEM), [152, 156, 154] (FDM), [163] (FVM)
OpenGeoSys	FEM	THMC	[144]
SEAWAT/MODFLOW/M3TDS	FDM	THC	[164]
TOUGH2/T2well	FDM	TH	[159]

Some software allow the users multiple solution methods; FEFLOW is a commercial finite-element code capable of simulating heat and fluid flux in the subsurface. It uses three methods for simulating heat flux in a BHE (1) it uses the hybrid semi-analytical approach [168, 169], (2) a novel 1D line element for the BHE often referred to as the 'dual-continuum approach' that uses thermal resistance to calculate horizontal heat flow (e.g.,[170, 171, 133, 134, 135, 144, 156]) and (3) full discretisation of the BHE and surrounding medium. Other software that support full discretisation (of the surrounding formation) include TOUGH2 [172], COMSOL [157, 173], MODFLOW [164], OpenGeoSys [174, 175, 176], and SHEMAT [177]. It is worth noting that the 'dual-continuum approach' [170, 171], is commonly used in numerical modelling of BHEs due to its high level of accuracy and significant reduction in computational time.

There are a number of studies on co-simulation, where detailed physical models are coupled to energy system tools. An updated version of TRNSYS which relies on Ground Heat Exchanger Analysis Design and Simulation (GHEADS) [178] for heat transfer modelling has been developed [179]. Compared to the default duct storage model in TRNSYS, GHEADS couples heat and moisture flow, accounting for the ground water table, as well as soil freezing and thawing cycles [180]. Welsch et al. [181] developed a co-simulation tool for BTES optimization in which FEFLOW is used for subsurface heat transport and the Carnot Blockset for MATLAB-SIMULINK is used for simulation of the surface components. In Shuang et al. [176], OpenGeoSys was used for subsurface heat transport modelling while TESPy [182] was used to model the surface components. Additionally, in non-UTES studies, TRNSYS and COMSOL have been coupled for hygrothermal effects [183]. Both open-source (e.g. MoBTES) [184] and commercial (e.g. Dymola) dynamic simulation tools have been built using Modelica. Modelica/Dymola can be coupled to COMSOL Multiphysics through Simulink S-Functions [185], or through a third-party tool, TISC suite [186]. Dahash et al. [187] developed a co-simulation tool which uses COMSOL for the STES model coupled to Modelica/Dymola through TISC suite. While the set-up worked properly, a major drawback is the large execution time observed. MoBTES was developed for modelling BHE systems in a modular structure making it possible to modify component types and modelling approaches. Several design features for BTES systems have been implemented including parallel and serial BHE connections, pressure loss calculation, reversal of flow direction, partially insulated BHEs and ability to consider stratigraphic subsurface models. It is to be noted that while MoBTES is a library, Dymola [188, 189] is a complete computer-aided engineering (CAE) modelling environment with a graphical user interface (GUI). MoBTES can be loaded and used in GUI-based CAE environments like Dymola and SimulationX[190] for which it has been tested. Dymola also has interface with other libraries like IDEAS library [191] and Buildings library [192] which can be used for BTES simulation. See e.g. [193] for a general overview of other relevant Modelica libraries. zerOBNL [194, 195] is an open-source co-simulation tool that has been made available recently. Several modelling and simulation environments were used and integrated into zerOBNL including EnergyPlus and TRNSYS [196]. Specialised software coupling tools like preCICE [197] can also be explored for co-simulation.

5.1.2. Aquifer Thermal Energy Storage (ATES)

Many studies have used detailed physics modelling tools for the subsurface of ATES systems without linking them to energy system tools which model surface components (e.g., [198, 147, 137]). Some studies have simplified the problem by considering a numerical model of ATES using MODFLOW and an analytical solution to a heat pump [138]. Similarly, Tugores et al. [199] simplified the physical modelling approach by producing a 1D numerical model, coupled to Modelica libraries.

Simplified axi-symmetric models in TRNSYS based on finite-differences have been compared with FEFLOW and results suggest the difference in heat recovery to be minimal [200]. The authors of this study did, however, suggest that modelling of the wellbore must be considered when investigating varied pumping rates and heat sources - which is important to STES studies. It is also likely that the TRNSYS modelling would not be suitable for complex geological domains or when there will be thermal interference between wells. However, there is limited modelling of ATES in energy system tools and further co-simulation studies between detailed subsurface and surface models is required.

Co-simulation studies interfacing a detailed physics tool to model ATES and a building model have been undertaken. Bozkaya et al. [120, 121] and Bozkaya and Zeiler [122] coupled the numerical solver (COMSOL) to a whole-system modelling tool (TRNSYS) using a coding platform as a mediator (MATLAB). Rostampour et al. [139] used MATLAB for building models, NetLogo for ATES planning, MODFLOW for subsurface geo-dynamics and Python to interlink all models.

STES studies utilise a range of energy system tools, detailed physics tools, and co-simulation tools. While energy system tools use simplified numerical and analytical solutions, they have been proven to be accurate and efficient. For more complex geological solutions, detailed physical models can be used on their own or used in co-simulation concurrently with energy system tools. For scenarios with high data quality and quantity, data driven models involving machine learning may also represent the best method for subsurface and surface coupling [201].

5.2. Electrical Power System Modelling Tools

This section explores the use of electrical power system modelling tools in multi-sector analysis and co-simulation with the aim of carrying out smart energy systems analysis. Electrical power system modelling tools model the electrical grid at transmission and distribution scales [202], and connected components such as demands and generators. They are used to undertake a range of power system analysis such as load flow, stochastic security analysis, electricity markets, transient stability, and small-signal stability [203]. Different timestep resolutions, from sub-second to monthly, are used in these tools depending on the type of analysis and required computational speed. Many studies, particularly in long-term planning studies, use representative periods instead of full (multi-)year simulations in order to reduce optimisation problem size and, consequently, computational time [204].

Historically, power system tools (e.g., DIgSILENT PowerFactory [205], MATPOWER [206]) have used a single time period for modelling network flows. These tools were developed before the challenges of integrating variable renewable power generation, and electrification of demands such as heat and transport. Newer energy system tools (e.g., Calliope [207], OSeMOSYS [208]) use multiple time periods to represent different weather and demand conditions which is suited to solving unit commitment for thermal power plants which are dispatchable and to optimise storage and other demand side management techniques. However, often these tools employ simplified modelling methods to represent electrical grids.

Models are emerging which bridge the gap between single sector power system tools and multi-sector energy system tools. The power system tool PyPSA [209] was used to build the model PyPSA-Eur-Sec, which the authors assert as the first open, spatially-resolved, temporally-resolved, and sector-coupled energy model of Europe, in order to study cross-sector and cross-border integration [210]. Results from this study indicated an import role for battery electric vehicles, power-to-gas units, and long-term thermal energy storage to facilitate the integration of variable renewable energy sources and reduce overall whole energy system costs. Multi-energy grid simulation incorporating electricity, heating, and gas networks has been performed using the open-source power system tool pandapower [211] in conjunction with the open-source piping grid simulation tool pandapipes [212]. In an illustrative example, these tools are used to demonstrate an operation strategy which controls decentralised heaters based on incidents of overloaded lines in the power grid [212].

Existing co-simulation studies have demonstrated the potential for integrating heat and electricity networks via multiple tools. Pesendorfer et al. [213] developed a hierarchical control approach for power-to-heat appliances using multi-grid analysis. Their work provides a framework for testing control strategies for hybrid thermal-electrical networks. They modelled a district heating network using Modelica libraries and an electrical distribution network using pandapower. Co-simulation of these tools used the Functional Mock-up Interface. Widl et al. [214] introduced a design approach that enables the analysis and optimisation of heat and electricity networks with the focus on analysing and testing control. Their study used a similar set of tools as Pesendorfer et al. [213]. Modelica libraries were used to model the district heating network and DIgSILENT PowerFactory to model the electricity network, while the Functional Mock-up Interface was used to integrate MATLAB and Python to enable co-simulation.

The studies discussed in this section include thermal storage in the form of hot water tanks, however the authors have not found any co-simulation studies which explicitly integrate BTES or ATES in a co-simulation process incorporating both heat and electricity network modelling tools.

6. Discussion and Conclusions

This paper has outlined three potential smart applications of STES, and reviewed approaches to modelling BTES and ATES within smart energy systems including using energy system tools and co-simulation with detailed physics tools and electrical power system tools. The paper starts with an overview of STES by describing key characteristics and case studies.

The first smart application, the utilisation of renewable energy sources, showcases STES as a flexibility option capable of integrating RES sources beyond the most common application of seasonally variable solar thermal. Locally sited variable RES, such as solar PV and wind turbines, as well as large-scale RES installations through a wider grid connection, such as offshore wind, can be stored as heat in STES through power-to-heat technologies such as heat pumps and electric boilers. Several studies have been undertaken which use short term thermal storage in conjunction with solar PV and wind turbines. However, there is a lack of studies which analyse the integration of BTES and ATES with RES technologies beyond solar thermal such as solar PV and wind turbines.

The second smart application is the potential for integrating waste heat and cooling. There is a potential geographical and temporal mismatch between waste heat and demands. Studies show that BTES can tackle these issues and increase the utilisation of waste heat. These studies typically used TRNSYS to model the waste heat, BTES, heat demands, and (in some studies) a CHP plant.

The third smart application is the provision of electrical network balancing at various timescales. Electrical network balancing is increasingly required as energy systems rely on higher penetrations of non-dispatchable RES. Thermal storage has been identified in literature as a useful component to allow sector coupling technologies such as heat pumps and CHP to provide intra-day balancing and frequency support. STES has received little attention in literature in regards to this application, likely due to low charging/discharging rates (particularly for BTES), however, there is potential for STES to enable other technologies to operate more flexibly. The authors believe that this should be considered in future studies.

Energy system tools with capability in modelling STES were categorised into either planning tools or detailed design tools. While several planning tools have the capability to model STES, they lack sufficient detail, realistic control strategies, and open-source code. Two simplified energy flow methods for simulating STES were identified in literature which could be incorporated into an existing open-source planning tool to address this gap. Several detailed tools were identified as capable of modelling STES, with TRNSYS emerging as the most popular tool. More studies were identified which analysed BTES compared to ATES, for which studies typically utilise detailed physics tools.

There are several studies on co-simulation of these detailed physics tools and energy system tools for both BTES and ATES. Detailed physics tools are suited for complex geological solutions, where they can be used on their own or in co-simulation with energy system tools. Data driven models are emerging which may be used to develop higher accuracy models of STES [201].

Power system tools and models are emerging to bridge the gap between traditional single-sector focused tools and whole energy system models. These may explicitly incorporate energy sectors, such as heat, within the tool, or co-simulation methods coupling power system tools with thermal models. Many studies include short term thermal storage, but no studies were found which look to explicitly integrate BTES or ATES in a co-simulation process incorporating both heat and electricity sector modelling tools. Therefore, research is required which models heat and electricity networks alongside STES to enable analysis of the smart applications of STES discussed earlier in this paper.

In conclusion, this paper has outlined three smart applications (utilisation of renewable energy sources, integrating waste heat and cool, and electrical network balancing) to showcase the important role of STES in smart energy systems. Modelling approaches for sub-surface STES, both BTES and ATES, have been reviewed. Energy systems tools were categorised as planning and detailed design tools, and the information gathered can be used to inform tool selection. Gaps were identified for planning tools in relation to detail, control, and open-source of code, and for detailed design tools, TRNSYS emerged as the dominant tool to model BTES with less studies in literature for ATES. Co-simulation offers a promising avenue for modelling STES in smart energy systems. Several studies were reviewed which combine detailed physics tools, to model subsurface heat transfer, and energy system tools. There are studies which combine power system tools with energy system tools possessing thermal modelling capability. However, a gap exists for a modelling methodology which explicitly integrates BTES or ATES in a co-simulation process with both electricity and heat sector modelling tools.

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