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Electricity, gas, heat integration via residential hybrid heating technologies – An investment model assessment

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ABSTRACT

Integrating gas, electricity and residential heating sectors through hybrid heating technologies equipped with smart controls could provide energy system planning and operational benefits. Hybrid heaters combine different heating appliances in one device and can switch between those appliances during operation. Different configurations are possible: B-R (gas boiler-resistance), HP-B (heat pump-gas boiler), and HP-R (heat pump-resistance) heaters. A linear programming investment model is formulated and applied to an Irish test system with 40% wind energy generation to determine the optimal capacities and dispatch for the power and residential heat systems, including thermal storage. No technology is a silver bullet, but this paper finds that the widespread deployment of hybrid HP-B systems delivers a wide range of cost and strategic benefits: This hybrid technology minimises total system cost, reduces gas consumption and CO_2 emissions compared to B-only, and, compared to HP-only, reduces power generation capacity requirements and heater capital cost. Other hybrid heaters are effective in addressing a specific challenge, although with drawbacks: Hybrid B-Rs considerably reduce wind curtailment, but increase the use of carbon-intensive coal generation; HP-Rs mainly only benefit consumers by reducing heater capital cost compared to HPs and require more generation capacity additions and thermal storage tanks.

1. Introduction

Space and water heating demand represents roughly 80% of final energy use in residential buildings in Europe and 60% in the US (United States) [1]. Natural gas is the fuel of choice for heat provision in many cases today. However electrification of heat, mainly using highly-efficient HP (heat pumps), is increasingly supported in the EU (European Union) due to security of supply concerns and carbon emission reduction targets [2]. The future development of the residential heating system should not depend on heating technology alone, but, in a more complete analysis, on system-wide integration challenges, compatibility with existing infrastructure and the multiplicity of stakeholders' perspectives. Electric utilities are concerned about increased peak demands and reduced annual average asset utilizations of the power system [3]. HP adoption rates in the EU have fallen behind expectations [4] and the market is limited to new or retrofitted buildings where the installation is economically justified by installing smaller HPs and consequently lowering the HP investment.

Hybrid heating technologies are multi-energy devices [5,6] that combine different heating appliances: natural B (gas boiler), HP and R (resistance heaters). These devices can switch during operation between the appliances [7]. If equipped with smart controls, hybrid heaters could integrate gas, electricity and heating systems and provide additional power system flexibility, which is required to balance supply and demand and to accommodate the rapidly increasing share of variable renewables, mainly wind and solar PV (photovoltaic) [3,8]. Hybrid HP-B (heat pump-gas boiler) and B-R (gas boiler-electric resistance heaters), for example, have the ability to switch from gas to electricity for generating heat at times of excess renewable electricity on the power grid that would otherwise be curtailed and – vice versa – at times of peak electricity demand, they have the ability to switch from electricity to gas.

An increasing number of manufacturers in Europe and the United States have commercialised hybrid HP-B systems since 2010 [9–11], but the hybrid heater market remains a niche. Recent research on hybrid HP-B systems has established the direct

Abbreviations: B, gas boiler; B-R, hybrid gas boiler-resistance heater; CCGT, combined cycle gas turbine; HP, heat pump; HP-B, hybrid heat pump-gas boiler; HP-R, hybrid heap pump-resistance heater; OCGT, open cycle gas turbine; R, resistance heater.

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consumer benefits for single-house installations [12–14]. Klein et al. [12] develop a full-year simulation model of the space heating system for a 1970s house and its retrofitted variant in Germany, demonstrating that hybrid HP-B heaters reduce operational costs for consumers compared to air-source HPs. The efficiency of air-source HPs decreases with colder outdoor temperatures with all other conditions, including supply temperature, kept constant. As a consequence, HPs tend to be over-dimensioned for most of the remainder of the heating season except if a gas boiler is used in a hybrid configuration as an additional second heat generator to operate during the coldest fraction of the heating season. Park et al. [13] come to a similar conclusion for water heating in Korea. Hybrid heating technologies can also be installed in older houses without deep retrofit of the building insulation or the heat distribution system [15]. The compatibility of new heaters with the existing building stock is important given that at least 75% of the existing buildings will still be standing in 2050 in the United States and Europe [16]. Li et al. [14] determine the optimal operation strategy for a system composed of a large hybrid HP coupled with a gas boiler in a community-level district in China composed of residential and commercial buildings. They find that the hybrid system could reduce primary energy consumption by nearly half and considerably reduce operating cost compared to a coal-fired heating system, but do not offer a comparison against HPs.

Electric heating systems, such as a HPs, convert electricity input to heat output – thus linking the residential heat demand to electricity sector. Since electricity systems need to be balanced in real-time based on variable demand and increasingly variable supply due to penetration of renewables, the deployment of electric heaters will impact system dispatch in the short-term and, in the long run, the electricity generation portfolio. Energy systems research, however, has not previously considered the contribution of hybrid heating technologies. Vuillecard et al. [17] indicate in their field experiment analysis on power system benefits of micro-CHP, that hybrid HP-B systems could manage electric peaks by switching from electricity to gas during peak times. Capuder and Mancarella [18] optimise the operation of multi-generation devices – including HPs, combined heat and power and thermal storage – in district energy systems and derive some investment benefits. They do not analyse HP-based hybrids and do not optimise internally system-wide decisions, such as capacity expansion and electricity dispatch.

Existing energy systems research in relation to electricity and heat largely focusses on system planning impacts of HP technology [19–21] and district heating integration [22]. Kiviluoma et al. [19], in a case study of Finland, and Hedegaard et al. [20,21], in a case study of Denmark, find that HPs can provide power system flexibility to support wind integration if equipped with thermal storage. The heat-power system is modelled using the linear least-cost investment model *Balmoral* [19,21], and the simulation model EnergyPLAN [20]. Hedegaard et al. also add that the thermal inertia of the building envelope itself could be utilised as a thermal store in an energy efficient building [21]. The investment models in Refs. [19,21] use an hourly resolution model, but for a few representative weeks of the year. District heating systems are often touted as the key link between electricity and residential heat to provide operational flexibility for many regions, such as the Nordic countries [22]. However, district heating systems are not suitable for all regions, mostly due to their high capital requirements, long construction times and population density requirements [23,24]. Hybrid heaters could provide an alternative to district heating networks to interconnect the power and heat sectors.

The planning impact of hybrid heaters if deployed at scale has not been studied in existing literature. This paper assesses the value proposition for different hybrid heating technologies (B-R, HP-B and HP-R (hybrid heat pump-resistance heater)) on a holistic level in the context of a future energy system with high shares of variable renewables; The Republic of Ireland is used as a case study. The system-wide approach captures the planning and operational benefits in both the power and residential heat sectors, in a combined manner. A least-cost investment model covering the power generation and residential heat sectors, including thermal storage, is developed. The model internally decides the optimal power generation, heat generation and thermal storage capacities, as well as the hourly power system dispatch and when to operate the different appliances of the hybrid heating system and the thermal storage tanks. The analysis uses an hourly resolution for a full year in chronological order to capture diurnal and seasonal variability and inter-dependencies of renewable energy generation, electricity and heat demand. This research focuses on the residential heating sector, but can be expanded to the industrial and service sectors. It is not necessary to model the gas system explicitly, because the gas network is balanced over longer time-frames than electricity and, in the EU, is also increasingly underutilised due to end-use efficiency, end-use electrification and displacement of gas power generation by near zero-marginal cost renewables [25,26].

The paper is structured as follows: Section 2 introduces residential heating technology and related system challenges. In Section 3, the least-cost investment model that jointly optimises electricity and residential sectors is formulated and the Irish test system is introduced. Section 4 presents the results for the case studies and discusses the significance of the outcomes for a wide range of stakeholders including system planners, technology developers, aggregators and consumers. Section 5 draws some compelling conclusions that could be used to inform future system planning decisions.

2. Characteristics of residential heaters

The underlying technical and economic characteristics of different heating technologies directly impact the integrated electricity-natural gas- and residential heat system (Fig. 1). For the EU and US, three main single-technology options can supply space and water heating: boilers, resistance heaters and HPs. Boilers can be fuelled by a variety of fuels including natural gas, oil and biomass, but this analysis is limited to natural gas. In some countries oil boilers and wood burners are prevalent, but we expect that the hybrid concept can be applied in that context also. Combined heat and power plants, geothermal and district heating systems are out of the scope of this analysis.

- Natural gas boilers (B) are commonly used due to their low investment cost, relatively low fuel cost, high efficiency (96–98% for new condensing boilers) and the minimisation of local pollutants [27].
- Electric HPs use ambient heat, mainly from air- or ground-sources, and transfer the heat to the building via a refrigerant. HPs only use electricity to drive the auxiliary equipment (i.e. pump, compressor and fans), so that a single unit of electricity input translates into multiple units of heat output. The resulting high process efficiency is quantified by a COP (coefficient of performance) around 2.6–4 for air-source HPs and 3.5–5 for ground-source HPs [15,27,28]. Investment costs of HPs are considerably higher than for gas boilers (Fig. 2), even though the higher efficiency reduces the required heater capacity. This study focusses only on air-source HPs since they are more affordable than ground-source HPs and have been more widely deployed in the past [4].
- Electric resistance heaters (R) convert electric current passing through a resistor into heat. Although this end-use process itself

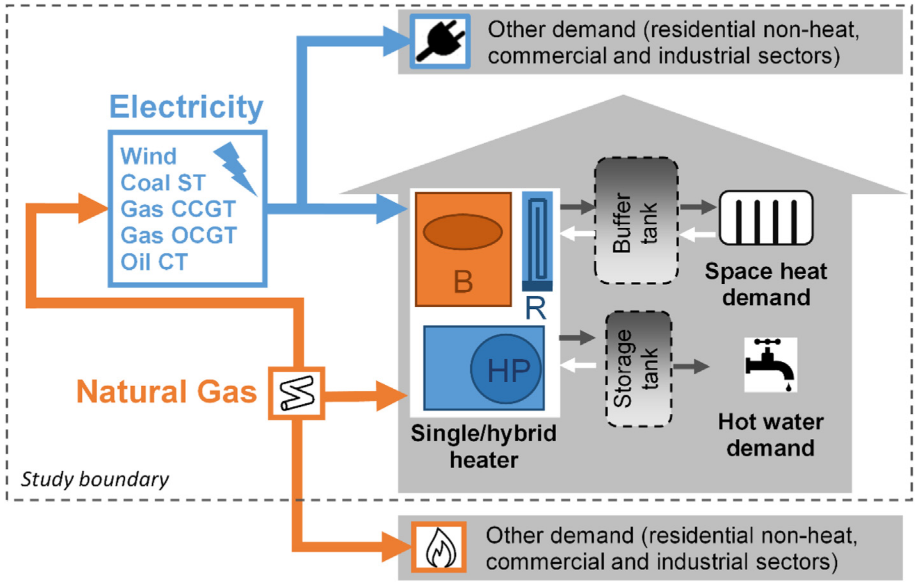


Fig. 1. Schematic of the integrated power-residential heat system studied.

is nearly 100% efficient [27], the whole value chain efficiency that includes power generation, transmission and distribution is considerably lower, implying that HPs are generally considered the preferable future option due to their higher overall efficiency [2,16]. The use of electric resistance heaters in a single-technology configuration is excluded from this analysis and only considered as a component for hybrid heaters.

These technologies can be combined into different hybrid heaters: B-R, HP-B and HP-R configurations for example. Hybrid B-R heaters use the gas boiler as the primary heating source and a switchable resistance heater as a secondary source. The resistance heater can be positioned either in the return line to the boiler or in the storage tank (if available) [7,29]. The upfront costs of B-R heaters are relatively low since they are based on two relatively low-cost technologies. The B-R system can also be integrated into existing gas boilers.

In hybrid HP-B and HP-R systems, the gas boiler or resistance heater respectively, complements the HP when additional heat is needed during the coldest fraction of the heating season. In fact, air-source HPs operate most efficiently when the temperature difference between heat source (i.e. outside ambient air) and heat sink (i.e. indoor heat circulation system) is lowest, because less mechanical work is required to move heat from the cold source to the warm sink (based on the Carnot cycle COP). This means that during relatively cold temperature spells (below 0 °C, for example) when heat is most needed the HP efficiency is below its rated COP (often measured at 7 °C). The HP in a hybrid can be downsized compared to HP-only systems and thus investment costs are lowered. Commercial HP systems often already include a small resistance heater to supply peak heat demand [30].

If real-time electricity pricing is enabled through smart control, all hybrid systems could shift between the different appliances depending on market conditions. When low-marginal cost

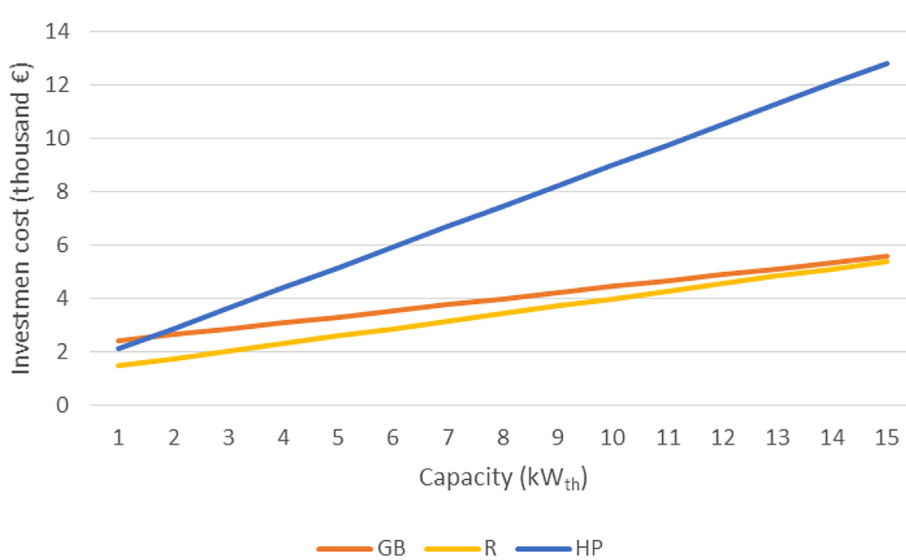


Fig. 2. Investment cost for different heaters in function of capacity.

electricity (e.g. wind or solar PV that would otherwise be curtailed) is available on the power grid, the hybrid heat systems choose to use electricity to meet residential heat energy demand. During times of peak electricity demand, the hybrids with a gas component (HP-B and B-R) can switch from electricity to gas to avoid price spikes and, in the long-run, reduce the need for electricity generation expansion.

3. Methodology and test system

3.1. Model description

Based on a capacity expansion planning methodology, a least-cost investment model covering the residential heat and power sectors is developed. The one-stage planning model includes both capital and operational expenditure for power generation, heating technology and thermal storage. Capital costs include technology investment and fixed O&M (operational and maintenance) cost. Operational cost include fuel costs, variable O&M and carbon costs. The model depicts generation, demand and storage state variables hourly and in chronological order to capture wind characteristics as well as diurnal and seasonal demand variability for both power and heat. For hybrid heaters (B-R, HP-B and HP-R), the model determines the optimal share of each appliance's capacity in the hybrid device, as well as the dispatch between the different heat appliances based on least-cost operation. Generation technologies are dispatched as technology groups rather than individual plants. Due to the hourly representation for a full year, the investment decisions are based on internally calculated operational hours and not on estimated utilisation factors. Considering the lack of existing literature around system analysis of hybrid heating technologies, the model was written as a linear program to allow quantification of benefits across the whole system, while also favouring computational speed. The model is assumed to have perfect foresight, which means operational uncertainties are not mathematically captured. A detailed operational timeframe analysis would require a stochastic operational model to be embedded in the investment model, which is computationally extremely challenging. The impact of the perfect foresight assumption is modelled as part of a sensitivity analysis.

The optimization algorithm in equations (eqs. (1)–(17)) minimizes total system costs and will endogenously determine the decision variables: capacity C ([MW]) and energy generated E ([MWh]) for each electricity and heat generation technology, as well as thermal storage tanks, referred to with superscript *elec*, *heat* and *sto*, respectively. All capacities and energy generation are defined in terms of output. Power generation technologies *PTech* considered are wind, coal, combined cycle gas turbine, open cycle gas turbine and oil combustion turbine, along with heat technologies *HTech* including B, HP and R.

The objective function (eq. (1)) computes total system cost and is composed of total annualized investment, fixed annual O&M, fuel, variable O&M and cost expenditure for both power generation and residential heat, based on specific investment cost IC, fuel prices FP, carbon emission factors CF, carbon price CP, number of residential households n, capital cost for smart controls $IC_{IT\&Com}$ for hybrid heaters and an annuity factor a (eq. (17)).

$$\min\left(\sum_{PTech}\left(\underbrace{\left(IC^{elec}_{PTech}\Big/a^{elec}+OMFix^{elec}_{PTech}\right)\cdot C^{elec,new}_{PTech}}_{investment\ cost\ elec.}+\underbrace{\sum_{t=1}^{8760}\left(FP_{PTech}/\eta_{PTech}+OMVar^{elec}_{PTech}\right)\cdot E^{elec}_{PTech}(t)+CF^{elec}_{PTech}\cdot CP\cdot E^{elec}_{PTech}(t)}_{opererational\ cost\ elec.\quad (incl.\quad elec\quad heat)}\right)\right.$$
$$+n\cdot\left(\underbrace{\sum_{HTech}\left(\begin{array}{l}\left(IC^{heat,equip}_{HTech}\Big/a^{heat}+OMFix^{heat}_{HTech}\right)\cdot C^{heat}_{HTech}+IC^{heat,inst}_{HTech}\Big/a^{heat}\\ +c_{IT\&Com}+\sum\limits_{i=\{space,water\}}IC^{Sto}\cdot C^{Sto,i}\end{array}\right)}_{investment\quad cost\quad heat}\right.$$
$$\left.\left.+\underbrace{\sum_{t=1}^{8760}\left(FP_{HTech=B}/\eta_{HTech=B}\cdot E^{heat}_{HTech=B}(t)+CF^{heat}_{HTech=B}\cdot CP\cdot E^{heat}_{HTech=B}(t)\right)}_{opererational\quad cost\quad gas\quad boiler\quad (non-elec.\quad heat)}\right)\right)$$

The decision variables are subject to several constraints.

Electricity generated in each hour t needs to meet total electricity demand $D^{elec,\ total}(t)$ (eq. (2)) composed of the reference electricity demand $D^{elec,ref}(t)$ (residential non-heat, commercial and industrial sectors) and electricity demand to drive the electric heaters HP and R $D^{elec,4heat}(t)$ (eq. (3)). The electric heat demand $D^{elec,4heat}(t)$ interlinks the electricity and residential heat sector. As previously explained, the HP efficiency $\eta_{Tech=HP}(T_{outside}(t))$ is dependent on outside temperature $T_{outside}$ and is pre-computed, using a linear dependency based on HP performance data (eq. (18) as part of the test system description) and external ambient temperature data. Efficiencies for other heat technologies (B and R) are time-independent.

$$\sum_{PTech} E^{elec}_{PTech}(t) = \underbrace{D^{elec,ref}(t) + D^{elec,4heat}(t)}_{D^{elec,total}(t)} \quad \forall t \tag{2}$$

$$n \cdot \sum_{HTech=\{HP,R\}} \left(E^{heat}_{HTech} \Big/ \eta_{HTech}(T_{outside}(t)) \right) = D^{elec,4heat}(t) \quad \forall t \tag{3}$$

Total generation capacity is composed of existing and new built capacity (eq. (4)).

$$C^{elec}_{PTech} = C^{elec,existing}_{PTech} + C^{elec,new}_{PTech} \quad \forall PTech \tag{4}$$

No power (eq. (5)) nor heat (eq. (6)) technology can generate more energy than the installed capacity in each hour.

$$E^{elec}_{PTech}(t) \le C^{elec}_{PTech} \cdot 1h \quad \forall PTech \tag{5}$$

$$E^{heat}_{HTech}(t) \le C^{heat}_{HTech} \cdot 1h \quad \forall HTech \tag{6}$$

At all times, a capacity constraint ensures system adequacy for 105% of demand, considering the capacity credit $CCredit_{PTech}$ of each generation technology (eq. (7)) [31].

$$D^{elec,total}(t) \cdot 1.05 \le \sum_{PTech} C^{elec}_{PTech} \cdot CCredit_{PTech} \quad \forall t \tag{7}$$

Energy generated by each technology must not be greater than the installed capacity multiplied by its availability *Av* (h) to account for plant outages and maintenance (eq. (8)).

$$\sum_{t=1}^{8760} E^{elec}_{PTech}(t) \le C^{elec}_{PTech} \cdot Av_{PTech} \quad \forall PTech \tag{8}$$

Wind energy dispatched is limited by resource availability, defined by hourly capacity factors *CFac*(t) and the installed capacity (eq. (9)), and by the SNSP (system non-synchronous penetration) to ensure power system frequency and transient stability. *SNSP* is an instantaneous indicator, developed by the Irish grid operator, of the amount of non-synchronous energy generation (wind energy generation and HVDC imports) relative to demand on the system (eq. (10)). The Irish grid operator aims to ensure stable grid operation for instantaneous *SNSP* levels of up to 75% by 2020 [32].

$$E^{elec}_{Wind}(t) \le CFac_{Wind}(t) \cdot C^{elec}_{Wind} \quad \forall t \tag{9}$$

$$E^{elec}_{Wind}(t) \le SNSP \cdot D^{elec,total} \quad \forall t \tag{10}$$

A ramp-up and down constraint for coal and CCGT plants is put in place to capture technical ramping limitations (eq. (11)). Ramping limitations for other plants are not required for the hourly time resolution.

$$\left| E^{elec}_{PTech}(t) - E^{elec}_{PTech}(t-1) \right| \le RAMP^{MAX}_{PTech} \cdot 1h \quad \forall t, \quad \forall PTech \in \{coal, CCGT\} \tag{11}$$

On the heat side, a heat appliance will provide both space and water heating.

$$E^{heat}_{HTech}(t) = E^{heat,space}_{HTech}(t) + E^{heat,water}_{HTech}(t) \quad \forall HTech, \forall t \tag{12}$$

Heat demand for space $D^{heat,\ space}(t)$ and water $D^{heat,\ water}(t)$ is met by all heat generation technologies including natural gas boilers in each hour (eq. (13)). If thermal storage is built for space heating or hot water, the storage can be loaded $L^i(t)$ or unloaded $U^i(t)$.

$$n \cdot \left(\sum_{HTech} \left(E^{heat,i}_{HTech}(t) \right) - L^i(t) + U^i(t) \right) = D^{heat,i}(t) \quad \forall i \in \{water; space\}, \forall HTech, \forall t \tag{13}$$

The energy content in the storage tank is represented with a time-dependent state variable $E^{Sto,i}(t)$. The energy content of the storage over a time step depends on the difference between storage loading $L(t)$ and unloading $U(t)$ (eq. (14)), as well as the stationary heat loss γ. The storage level is limited by the storage capacity C^i_{Sto} ([litre]), expressed as volume to enhance pertinence for building installation using the specific heat capacity $c_{p,water}$ ([kJ/kg K]) and density of water ρ_{water} ([kg/litre]) and assuming a temperature difference $\Delta Temp$ with ambience of 20 K (eq. (15)).

$$E^{Sto,i}(t+1) = (1-\gamma) \cdot E^{Sto,i}(t) + L^i(t) - U^i(t) \quad \forall i \in \{water; space\}, \forall t \tag{14}$$

$$E^{Sto,i}(t) \le \frac{c_{p,water} \cdot \rho_{water} \cdot \Delta Temp}{3.6 \cdot 10^6} \cdot C^{Sto,i} \quad \forall i \in \{water; space\}, \forall t \tag{15}$$

An individual heating device is dimensioned to meet the heating peak of a single household heat demand $D^H_{Household}$. It is assumed that the heater itself needs to have the capacity to provide the maximum load without taking into account the potential energy stored in thermal storage tank.

$$\sum_{HTech} C^{heat}_{HTech} \ge \max\left(D^{heat}_{Household}(t) \right) \quad \forall t \tag{16}$$

The capital payments are annualised using an annuity factor which is defined by a discount rate *r* and the economic lifetime β of the investment:

$$a = \frac{1-(1+r)^{-\beta}}{r} \tag{17}$$

The model is implemented in GAMS and uses CPLEX as a solver. For one set of inputs, the optimal solution is generated on average in 5 min on a computer with a 3.5 GHz processor and 16 GB RAM.

3.2. Test system

The Republic of Ireland serves as an ideal test system for a low-carbon energy system due to its high penetration of wind energy and relatively weak interconnection to other systems.

In 2014, wind contributed 18% of annual electricity generation. Under the EU Directive on the Promotion of the Use of Renewable Energy (2009/28/EC) [33], Ireland is legally bound to produce 16% of the total energy consumed in heating, electricity and transport from renewable resources by 2020. To meet this overall target, the Irish Government has set individual targets for renewables for 2020: 10% in heat, 40% in electricity (mainly wind) and 10% in transport. Ireland is projected to achieve its 40% wind target, but unlikely to meet the targets in transport and heat [34]. National policy targets for 2030 have not been set.

The planning horizon analysed is out to 2030 for which national targets are not set yet. Considering the lifetime of power generation and heat technology, this planning horizon is long enough to capture new capacity additions while also making it possible to make reasonable assumptions about policy and market developments.

3.2.1. Power

Today Ireland's power mix is composed of wind, coal, peat, gas, oil and hydro. Electricity consumption is growing again since 2012 after a dip in 2008 due to the economic downturn. The electricity peak is 4.8 GW and generation capacity is 7.2 GW [35]. Along with economic growth rates of 2.2%–3.8%, electricity demand is assumed to increase by 1.5% annually [35] and, by 2030, will equal 34 TWh.

Compared to today's power generation capacity, it is assumed that 300 MW of coal and 500 MW of CCGTs will be retired by 2030 and that peat generation will be totally phased out. Wind deployment targets are often set by policies to minimize carbon emissions and improve imports. A wind capacity target of 6000 MW for 2030 is assumed. Hydro generation is relatively insignificant, and is therefore ignored for simplicity in this case study. Electricity interconnection is ignored to keep the study focused.

Reference input parameters are compiled based on literature, but individual parameter sensitivities will be carried out to capture the impact of uncertainties due to technology development, carbon prices and policy decisions. Cost and performance characteristics for power plants and fuel prices have been collected from several sources (Table 1) [36,37]. A gas price of 8.5 € per GJ (roughly the average 2014 level in Western Europe) and a potential 150% increase to 12.75 € per GJ are studied. Other fuel prices and non-heat electricity load data are sourced from the Irish system operator [35] (Fig. 3). Capital investment in the power sector are annualised with a discount rate of 6% to capture the value of capital.

All monetary data from cited studies are inflated to 2014 values using the consumers' price index (CPI) for the Euro group. All foreign currencies are converted into € using the annual conversion rate of the publication year of the different studies referenced.

3.2.2. Residential heat technology

Techno-economic data for the different heating technologies are given in Table 2 based on a literature review [15,27,28,38,39]. Fuel prices for electricity-driven technology are not fixed exogenous parameters (Table 2), but variable hourly electricity prices determined internally in the model based on market conditions. Since electricity market prices are available to residential consumers and since transport and distribution for electricity and gas are out of the scope of this paper, wholesale natural gas prices are also assumed for residential customers. This assumption is necessary to ensure that electricity and natural gas as a household fuel are treated equally and that comparisons are not biased. A specific regulation or stakeholder perspective could change this assumption.

The HP dependence on ambient temperature [K] is pre-computed using a linear relationship (eq. (18)). The slope m is determined based on HP performance data from Ref. [40]. An ambient temperature of 280.15 K (7 °C) is a common COP measure point in EU performance regulations (EN 14511). The y-intercept COP_{input} is fitted so that the curve meets the model input COP (given in Table 2) when the outside temperature is 280.15 K (7 °C).

$$\eta_{HP}(T_{outside}(t)) = COP(T_{outside}(t)) = m\cdot(T_{outside}(t) - 280.15) + COP_{input} \tag{18}$$

The performance data for the HP are chosen for a supply temperature of 45 °C, which can provide hot water for most residential usages and space heating in low-temp radiators. Space heating with older high-temp radiators (supply temperature >55 °C) would decrease the COP, while the use with underfloor heating (with supply temperature often as low as 35 °C) would increase the COP.

Investment cost of residential heaters need to take into account that specific investment costs are not constant for all capacity sizes. The investment cost of residential heating technology can be decomposed in installation and equipment cost. Only equipment cost can be assumed to scale with capacity for the residential heaters considered, whereas installation cost is independent of capacity. The cost breakdown for equipment and installation is assumed based on [27]. A linear cost representation (eq. (19)) for investment cost of heater $InvCost^{heat}_{HTech}$ is then derived with capacity-specific equipment cost $IC^{heat,equip}_{HTech}$ as slope and installation cost $IC^{heat,inst}_{HTech}$ as y-intercept.

$$InvCost^{heat}_{HTech} = IC^{heat,equip}_{HTech}\cdot C^{heat}_{HTech} + IC^{heat,inst}_{HTech} \tag{19}$$

Eq. (19) is integrated in the objective function (eq. (1)). The economic parameters used in the test system (Table 2) are mainly based on a single source [27]. The single-source ensures that the cost analysis has been carried out in a common framework for all technologies and therefore ensures that the relative difference between the technologies, which is the interest of this paper, is captured. The prospect for cost reductions in HP technology by 2030 is assumed only about 10% as the majority of components are drawn from a mature HVAC (heating, ventilating and air conditioning) market [41]. As part of the sensitivity analysis, the impact of an extreme technology breakthrough resulting in a halving of HP equipment cost is also assessed. B and R are mature technologies that are produced in large quantities, so the investment cost in 2030 is expected to remain at today's levels.

Investment cost of hybrids are assumed to be composed of the equipment cost of both appliances, but only of the installation cost of the most expensive appliance. This assumption takes into account that hybrid heaters are available as pre-assembled and commercial products. The installation of a hybrid does therefore not require to install both appliances individually, but rather connect the hybrid device as one product. The same logic is used for O&M cost. In order to allow hybrids to interact with the grid, an additional capital cost $IC_{IT\&Com}$ for the smart controls of 100 € is assumed, approximated based on the cost of a smart meter in Ireland [42].

Table 1
Techno-economic characteristics of power generation plants in 2030.

		Coal	CCGT	OCGT	Oil-CT	Wind
Capacity still in operation by 2030	MW_{el}	870	2360	780	770	1820
Efficiency	/	0.35	0.56	0.40	0.35	/
Investment cost	Million €/MW_{el}	2.2	0.8	0.65	0.7	1.5
O&M fixed cost	€/kW_{el} year	30	12	6.8	9.4	34
O&M variable cost	€/MWh_{el}	3.8	3.1	12.4	16.5	0
Fuel price	€/GJ_{fuel}	2.4	8.5/12.75	8.5/12.75	15	0
Carbon emission	kg CO_2/MWh_{el}	951	323	453	721	0
Capacity credit	/	0.99	0.99	0.99	0.99	0.15
Lifetime	years	30	25	25	25	20

Note: oil-CT (oil-fired combustion cycle), wind (onshore wind turbine), O&M fix (fixed operation and maintenance cost), O&M var (variable operation and maintenance cost).

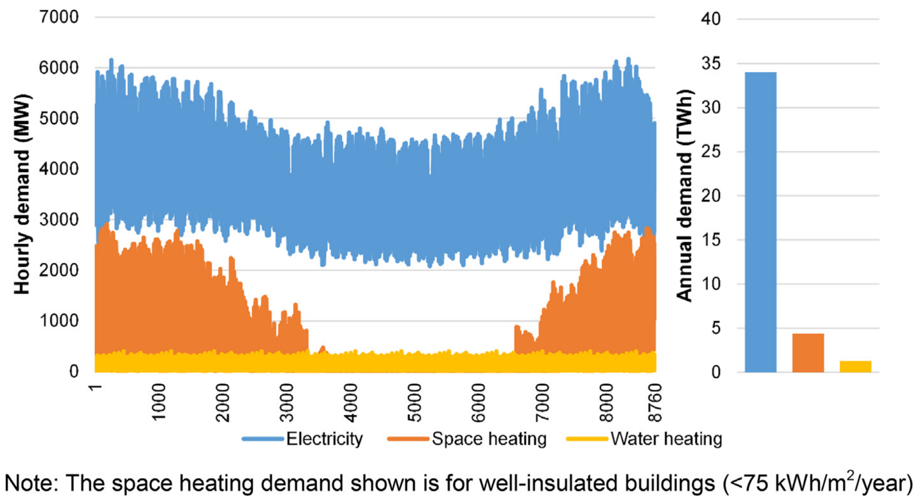


Fig. 3. 2030 hourly demand profile and annual demand for electricity in Ireland and residential heat for 400 000 well-insulated Irish households [35,46].

Thermal storage cost is set to 2.5 €/litre [20] and the capacity is limited to 500 L for space heating and 300 L for water heating. A stationary heat loss γ of 1% per hour is assumed in general (eq. (14)). The assumed model has perfect foresight of demand, but in practice imperfect foresight would lead to suboptimal charging and discharging patterns. As part of the sensitivity analysis a de-rated storage tank with a heat loss of 10% is considered in an attempt to emulate the effect of imperfect foresight of net electricity demand. Storage tanks should be heated to 55 °C once every week in order to avoid the appearance of legionella bacteria [43]. However this additional heat demand is ignored at this stage since the focus of the analysis is to compare the storage tank capacities chosen by the model for different heaters.

Capital investment in residential heating systems is annualised with a discount rate of 10% to represent the risk aversion of the private domestic sector and the increased cost of capital compared to large power generation investors.

3.2.3. *Residential heat sector*

Ireland has roughly 1.7 million households [44] categorized into five building types (bungalow, detached, semi-detached, mid-flat, top flat) [45]. Based on the size of a hybrid system and the type of commercial hybrid systems available today, the deployment of hybrid systems is more realistic in detached and semi-detached houses. It is assumed that 400 000 detached and semi-detached households (representing a quarter of all Irish households and half of these building archetypes) are equipped with the different heating technologies analysed: B, HP, B-R, HP-B and HP-R. The average annual heating demand for this building type is assumed to reduce in 2030 to the level of a new-built 2015 houses to represent energy efficiency improvements in the 2030 building stock. With typical standard occupancy assumptions, the annual heat demand is 11 MWh for space heating BER (Building Energy Rating) B1: <75 kWh/m^2/year and 3.2 MWh for water heating per household, down from 22 to 34 MWh for existing buildings today. A building stock where only the average annual heating demand is increased to 19 MWh (BER B3: <125 kWh/m^2/year), is also considered to analyse the impact of slower progress in building stock renovation or the impact in installing the heaters in less efficient houses. The full hourly aggregated heat profile is produced from metered data collected during a smart meter trial in Ireland covering 2000 households between 2009 and 2010 [46]. The initial data set records gas demand, so space and water heating were separated by assuming that the space heating season is limited between October and May [45] and that the monthly water profile is identical throughout the year. The use of metered data (Fig. 3) considers the diversity of load and depicts a representative peak load that directly impacts generation capacity investments.

4. Results and discussion

4.1. *Cost assessment*

4.1.1. *Total system cost in different long-term scenarios*

If comparing the results for five different heating technologies and a given set of other input parameters (from 3 carbon prices, 2 gas prices and 2 building insulation targets), then total system cost is lowest when hybrid HP-B heaters are deployed and highest when

Table 2
Techno-economic characteristics of residential heat technology in 2030 [27].

		B	R	HP
Efficiency	/	0.95	0.98	3
Investment cost − equipment $IC_{HTech}^{heat,equip}$	€/kW$_{th}$	225	280	765
Investment cost − installation $IC_{HTech}^{heat,inst}$	€	2200	1200	1500
O&M fixed cost	€/unit year	235	10	150
Fuel price*	€/GJ$_{fuel}$	8.5/12.75	Elec market	Elec market
Carbon emission	kg CO_2/MWh$_{th}$	242	/	/
Lifetime	years	20	20	20

Note: The HP COP is given for an ambient temperature of 7 °C.

HPs are deployed (Fig. 4). Other hybrid technologies also perform well: B-R heaters rank second; HP-Rs rank third for the high gas price and fourth for the low gas price scenario.

Total cost responds differently to changes in input parameters, based on the heater characteristics. Higher building insulation leads to lower system cost since less of both gas and electricity is required for heating. Rising gas prices have a stronger impact on the systems that heat with gas (HP-B, B-R and B). Carbon prices impact total cost less at low gas prices, which indicates that the energy mix is cleaner for low gas prices.

4.1.2. Cost breakdown for operational and capital cost in electricity and heat sectors

HP-B deployment leads to lowest total system cost, but the maximum difference between technologies with all other parameters being equal is only maximum 8–13% (Fig. 4). This is partially a result of the fact that base electricity demand for non-heating purposes is considerably larger (34 TWh) than the heating demand of a quarter of Irish households (5.7 TWh for low insulated houses and 8.9 TWh for high insulated houses, shown in Fig. 3). More pertinent than total cost is to understand how investment and operation cost change when different heaters are deployed and how the deployment of different heaters shifts costs between power and heat generation sectors, and also between the different stakeholders (household/power generation utility). The results in the following section will focus on the scenarios with the high carbon price (30 €/t) and high building insulation (<75 kWh/m2/year), unless stated otherwise.

The cost breakdown between investment and operational cost for electricity and heat for HP and hybrid heating technologies (B-R, HP-B, HP-R) is compared to the business-as-usual technology, gas boilers (B), for two different gas prices (8.5 and 12.75 €/GJ) (Fig. 5) and the carbon price and building insulation set previously. Only when hybrid heaters B-R and HP-Bs are deployed, do the savings from residential gas result in net savings (i.e. difference between savings and cost) for both gas prices (Fig. 5). In absolute terms, the net savings with HP-B heaters deployed (18–64 million € per year) are larger than the net savings with B-R (7–26 million € per year). With HP-Rs deployed, the savings amount to 60 million € annually in the high gas price scenario. However in the low gas price scenario, an additional cost of 40 million € is required. On a per household basis, the annual net savings are 46–159 € for HP-B, 18–65 € for B-R, depending on the gas price scenario, and 151 € for HP-R for the high gas price scenario only. The return on investment i.e. the savings compared to the additional investment are highest for the B-R system. HP deployment requires by far the largest investment mainly due to the high upfront cost of the heater, but also due to the additional investment in power generation capacity. The additional costs for all hybrids and HPs, compared to B, include operational cost for electricity, electricity generation capacity and the capital cost for the heater itself (including a storage tank as a potential investment option) (Fig. 5).

4.1.3. Power system investment

For the power system, the share of investment and operation cost switches between the low and the high gas price scenarios for the all-electric heaters (HP and HP-R). In the low gas price scenario, gas stations (CCGT and OCGT) are mainly added by the optimisation model (Fig. 6). This results in low investment cost and relatively high operational cost compared to wind and coal power plants. In the high gas price case, new coal generation is built (Fig. 6), which has the opposite cost composition: high investment and low operational cost. Coal-fired generation is relatively cheap in terms of fuel cost, and therefore the power system operation cost in the high gas scenario is relatively modest. This is true for the high gas price scenario even if a carbon price of 30 €/ton is considered, which indicates that this carbon price is not sufficient to encourage a switch from coal to lower carbon-emitting gas. Also, the operational cost in this scenario (high gas, HP or HP-R heaters) is lower than for the HP-B system since the power system with HP-B runs on a higher share of gas power plants with higher operational cost (established in Fig. 5).

The power system load duration curve illustrates how, during peak demand, electricity use is lowest for B, HP-B and B-R (Fig. 7) and therefore avoids or limits capacity expansion investments. At all times, including peak time, the reserve constraint (eq. (7)) requires the system to carry sufficient thermal reserve capacity. To meet this reserve constraint, new power generation can be added (mainly for HP) or electricity demand can be throttled (for B-R, HP-R and HP). In the latter case, electric heat demand is switched to the gas boiler for B-R or to the storage tank for HP-Rs and HPs, which results in a flattening of the load duration curve for critical peak hours (Fig. 7).

4.1.4. Heat system investment

The investment model internally determines the optimal operation and capacity of each of the different individual technologies that can compose the hybrid heaters, namely HP-B, B-R, HP-R:

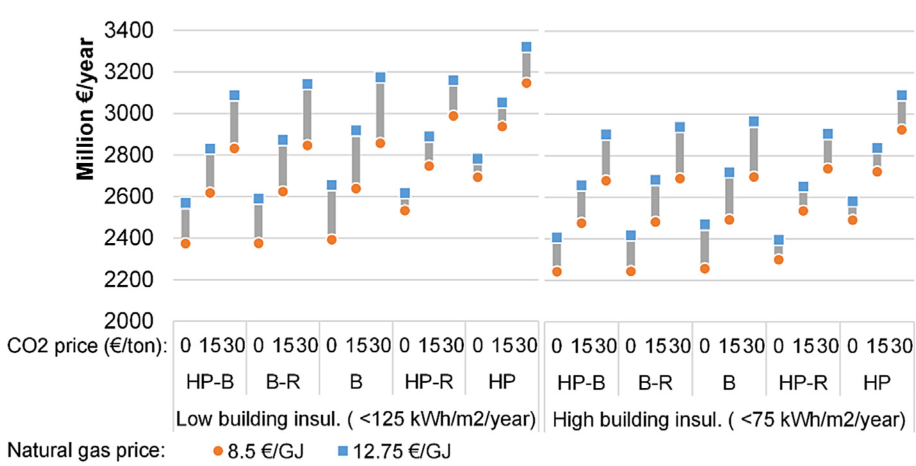


Fig. 4. Total system cost for different scenarios.

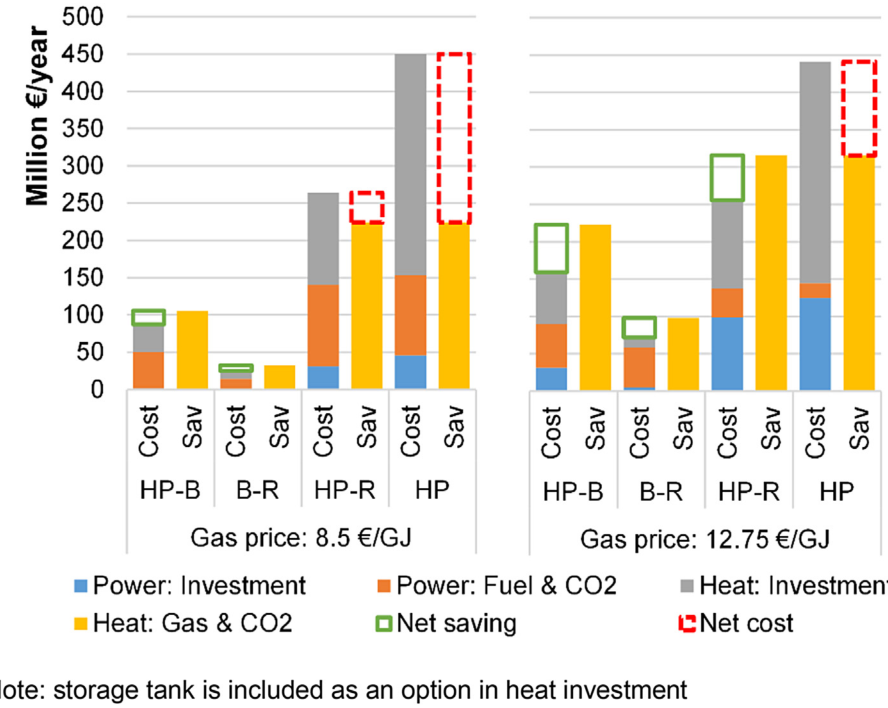


Fig. 5. Cost breakdown for deployment of different heating technologies (B-R, HP, HP-B, HP-R) relative to gas boiler (B).

- The heat pump in the HP-B system delivers around 47% of the heating energy at low gas prices and 70% at the high gas prices (Fig. 8). The gas fuel savings (established in Fig. 5) for the HP-B system are therefore still high compared to B, even if lower than for HP and HP-R. In terms of capacity, the HP represents 10% for the low gas price and 17% for the high gas price. The HP provides a considerably higher energy share than capacity contribution, which means that the heat pump, as a capital-intensive asset, is operated much more regularly throughout the year to maximise its utilisation. A technology breakthrough leading to a reduction in HP equipment cost by 50% would increase its contribution to heat generation to 80–90%. In such a case, Bs become only a back-up generator and HP-only systems lead to very low system costs.
- The B-R system switches to electricity whenever zero-marginal-cost wind and low-marginal-cost coal are available. The gas

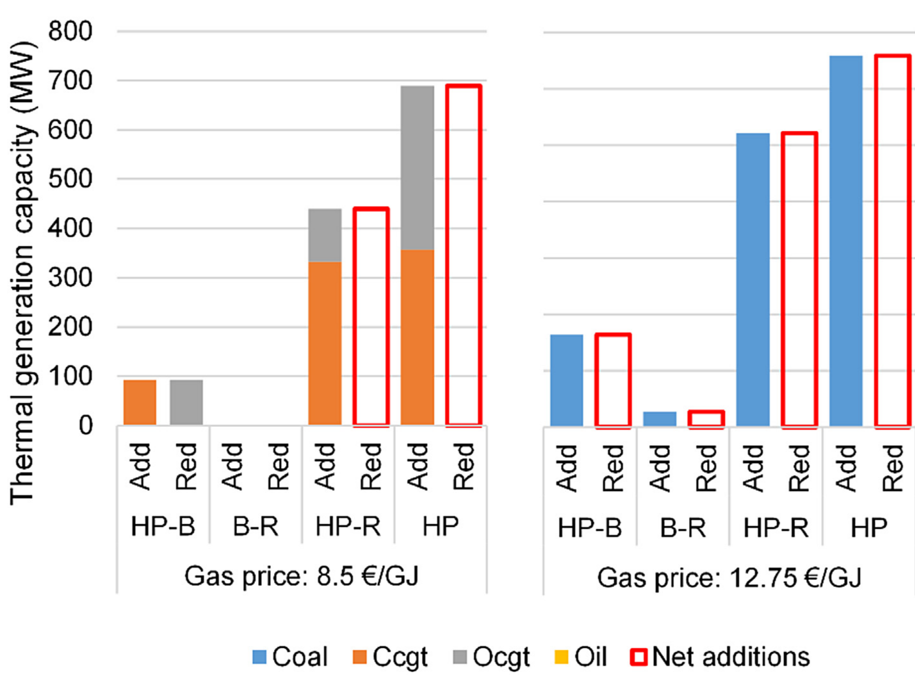


Fig. 6. Generation capacity for deployment of different heating technologies (B-R, HP, HP-B, HP-R) relative to gas boiler (B).

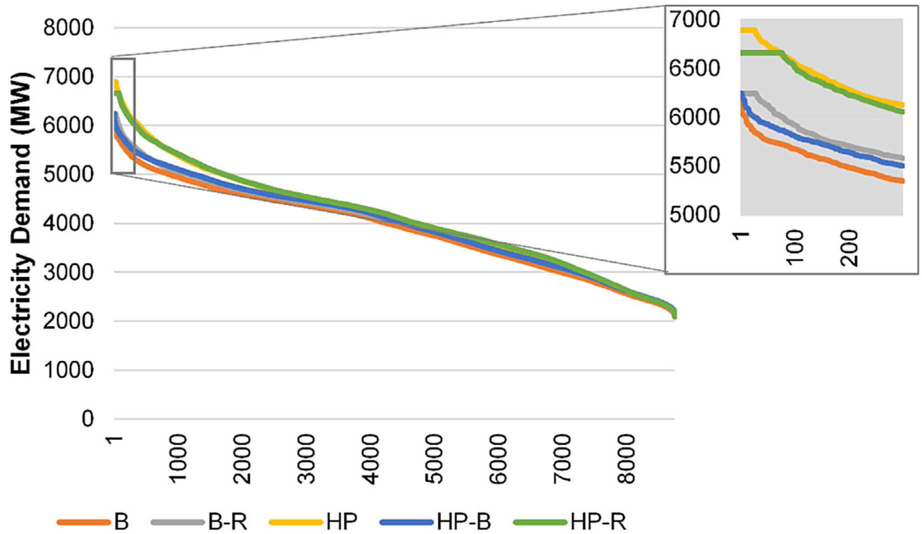


Fig. 7. Load duration curves for deployment of different heaters.

boiler of the hybrid B-R system remains the main energy source and delivers around 83% for the low and 76% for the high gas price (Fig. 8). This heat technology comes at minimal additional capital cost and could provide a significant return on investment from a total system perspective under the right circumstances.

- Hybrid HP-R systems, in comparison to pure HP systems, have a similar impact on the power system. The main benefits appear on the consumer side by reducing technology capital cost and providing additional backup during the coldest fraction of the heating season or times with very high heat demand. The hybrid HP-R system produces the majority of its heat from the heat pump (95%, Fig. 8). The R heater is used in combination with two very significant storage tanks (500 L for space heating and 120 L for water heating) to match generation and demand while minimising HP capacity.

B, B-R and HP-Bs require no or very little storage tanks (Fig. 9), which is an important practical benefit if space or weight limitations exist in the house. For HP-R systems the storage tanks required are very large. Given that the model has perfect foresight, the storage investments are sized and operated to fit the given demand profile. In reality, net demand is not known and operational uncertainty will result in suboptimal sizing. The use of a de-rated storage tank, with 10% stationary heat losses per hour is an attempt to emulate the influence of imperfect foresight (Fig. 9). In the scenario with de-rated storage, the HP capacity and its

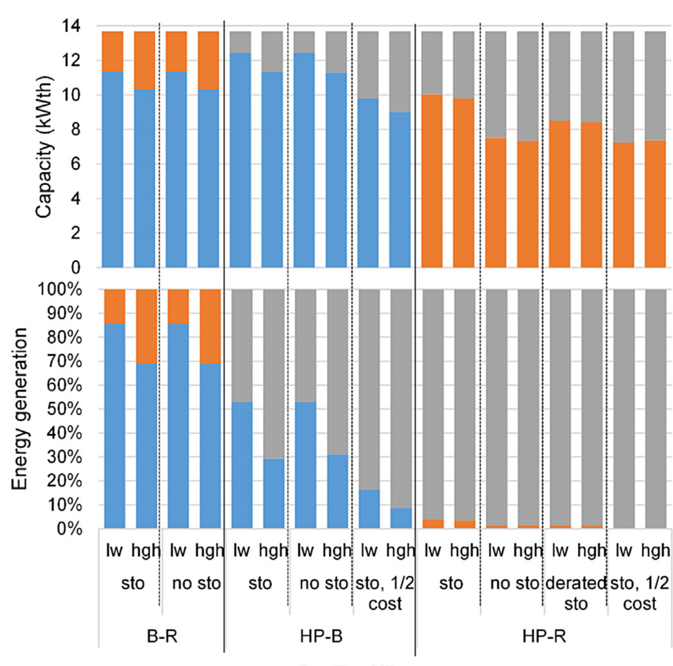


Fig. 8. Capacities and generation share of appliances of hybrid heaters (for well-insulated buildings and a carbon price of 30 €/ton).

generation share are increasing in order to compensate for the less-efficient storage tank or, in an analogous manner, to compensate for forecast uncertainty.

4.2. Strategic and non-economic assessment

Total system cost is a very important indicator in assessing energy policy strategies in terms of economic competitiveness and affordability, but other non-economic and strategic indicators are required to reflect the multiplicity of objectives often competing in energy policy, including climate change mitigation and energy security. Additionally, for any demand technology, successful consumer adoption of new technologies is critical.

Wind integration is being promoted to reduce CO_2 emissions and increase energy security. Wind curtailment is necessary, to a certain degree, for safe and economic system operation, but excessively high rates indicate inflexible and inefficient system design and constitute a key investment risk to wind developers. In the system analysed, wind curtailment could increase to more than 12% if no electric heating is deployed i.e. with B only (Fig. 10a). Heating electrification using all technologies increases flexibility and reduces curtailment considerably, but hybrid B-R systems outperform all other technologies. For low additional investment cost for the R element, an important amount of zero-marginal wind can be utilised. The HP-B's contribution to wind curtailment reduction is smaller, because it is constrained by the smaller HP capacity and lack of thermal storage.

HP and HP-R systems (HP-B, HP-R, HP) reduce CO_2 emissions significantly in the low gas price scenario, but increase emissions in the high gas price scenario since the share of coal in electricity generation increases (Fig. 10b). HP-B heaters offer modest to minor savings in both fuel scenarios, since the electricity generation capacity varies less for different fuel prices. The B-R system tends to slightly reduce or increase CO_2 emissions: it switches to electricity when wind and also low-marginal-cost coal is available rather than using less-polluting natural gas; this outweighs its positive environmental contribution in integrating wind (Fig. 10a). Regulation would probably be needed if these heaters were to be deployed to simultaneously reduce wind curtailment and CO_2 emissions, since the carbon market does not deliver the switch from coal to gas at the price of 30 €/ton assumed here.

Natural gas in Ireland is nearly entirely imported, making natural gas consumption a concern in terms of energy security. HPs and HP-Rs are the most effective in reducing natural gas consumption due to the high HP efficiency (Fig. 10c). Despite the negative effect of the gas boiler in HP-B hybrids, they still deliver a considerable gas consumption reduction, relative to B.

Householders, potentially supported by public programs, are required to bear the investment cost of new heaters unless alternative business models are applied, for example where utilities or aggregators lease the heaters to their customers. High investment costs often act as barrier for technology uptake due to short-term preferences and the cost of capital. The HP investment cost is more than double that compared to a simple B. Hybrid HP-B and HP-R heaters are only 13–24% and HP-R 35–37% more expensive than Bs (Fig. 10d). B-Rs are only marginally more expensive then Bs. The hybrids could therefore considerably lower the investment barrier for consumers to move away from gas boilers.

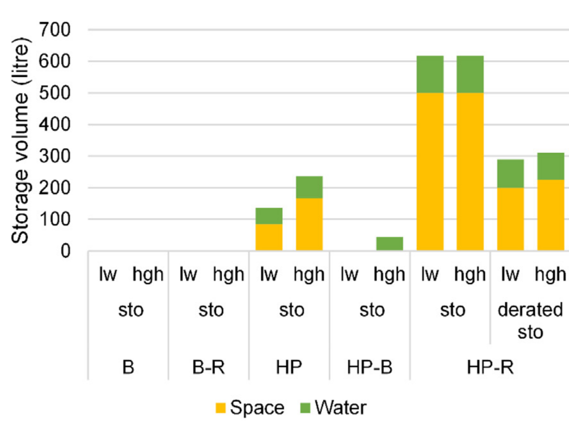
The consumer's preference for a residential heating system also depends on non-technical characteristics, which are not examined in detail. Space and aesthetics are likely to impact some consumer decisions. Both HPs and hybrid HP-B require an outdoor unit to be fitted to the outside of the building which may be perceived negatively. Hybrid HP-Bs require more space than HPs due to the additional appliance involved, while gas boilers require the least space. HP-B heaters avoid the need for the bulky, heavy thermal storage tank required with HPs and hybrid HP-Bs (established in Fig. 9).

4.3. Insights in heater and power system operation during critical week

Due to the overall good performance of HP-B heaters, the operation of heat and power systems with these heaters deployed is visualised for a critical week (for the lower gas price of 8.5 €/GJ and the well-insulated house; no storage tank is built for these parameters). In a February week, illustrated in Fig. 11, the wind output drops for an extended period of more than five days and the electricity demand is nearly as high as in the peak week. OCGTs are operated during a large part of the day and extend the periods with electricity prices spikes. However the marginal cost of heat system is set by the gas boiler and thus is not affected by price peaks. The HP-B system minimises the exposure of heat provision to electricity price spikes.

4.4. Overall assessment

The cost and strategic assessment (Section 4.1 and 4.2) confirm that hybrid heaters can provide some system-wide benefits compared to single-fuel heating technologies. This is true even if



Note: lw: low gas price; hgh: high gas price; de-rated sto: storage enabled but with 10% stationary losses

Fig. 9. Storage capacities build for different technologies (for well-insulated buildings and carbon price 30 €/ton).

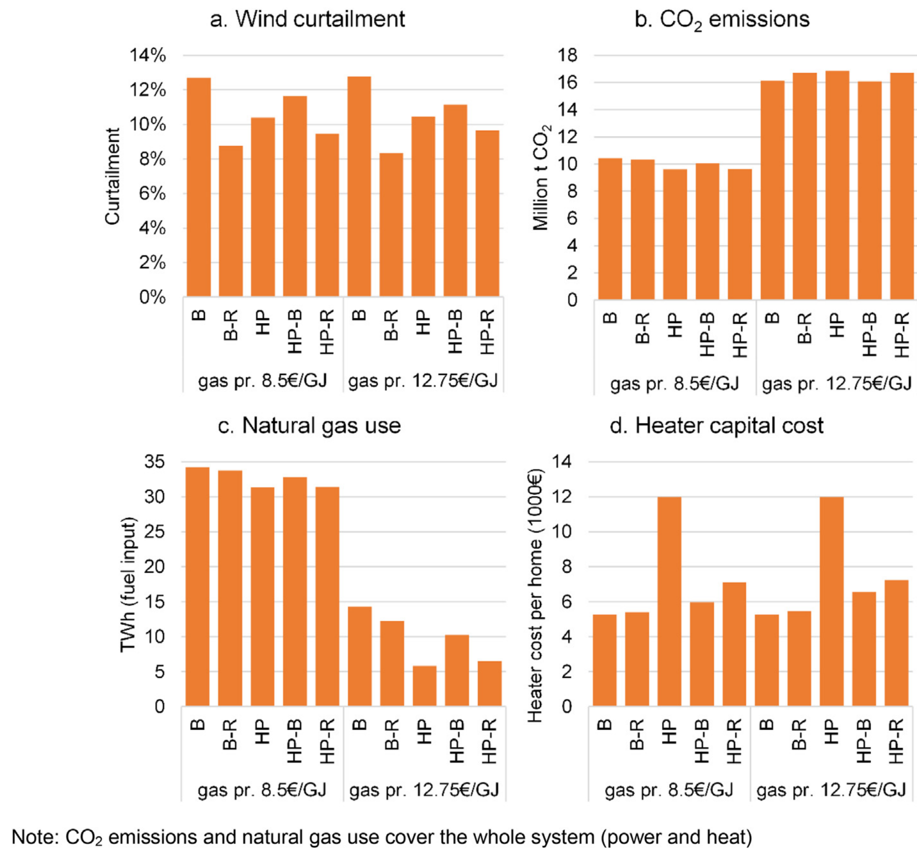


Fig. 10. Strategic and non-economic indicators: (a) wind curtailment, (b) CO_2 emissions, (c) natural gas consumption and (d) heater cost.

only a quarter of Irish households are considered (as in this paper) and if commercial and industrial heat demands are ignored.

For system planners, the analysis confirms that hybrid HP-B and HP-R technologies are an option to strategically interlink the power, heat and gas sectors and take advantage of the flexibility in the heat and gas systems. Hybrid heating systems equipped with smart controls can be considered as an alternative to district heating networks to integrate power and heat systems.

For technology developers and demand response providers, the results provide information about technology design requirements and potential business cases. Heating technology manufacturers should design hybrid heaters that can be aggregated in a smart, real-time manner based on price or renewable electricity availability to provide power system benefits. The resistance heater in the B-R heater should be dimensioned to maximise wind penetration while the boiler integrated into the HP-B should minimise peak load increase.

No technology analysed is a silver bullet that excels in all criteria. However, hybrid HP-B heaters perform well over most economic and strategic indicators. Their deployment minimises total system cost and, concurrently, reduces CO_2 emissions and gas consumption compared to B-only and invites only a small to

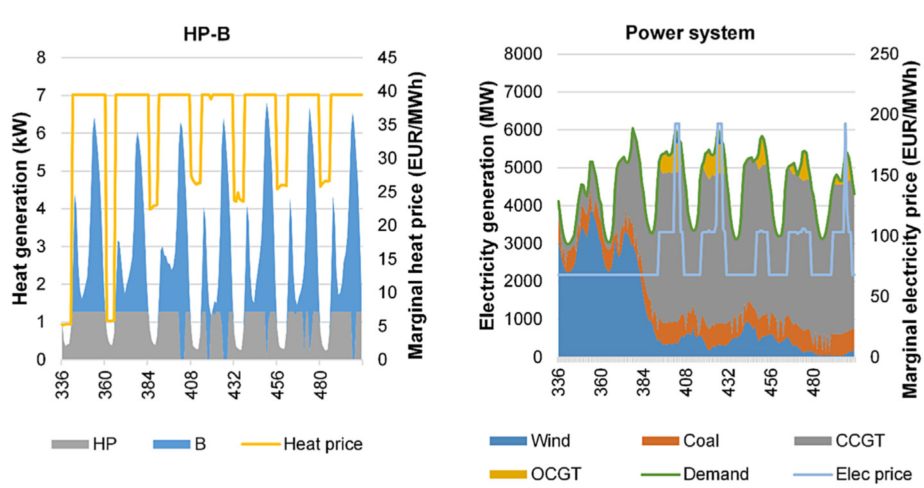


Fig. 11. Operation of hybrid HP-B and power system dispatch during the week with lowest annual wind output.

moderate penalty compared to HPs. The HP-B heating system is also less expensive than simple HPs and helps consumers to overcome the upfront investment cost barrier. Because the business case also depends on the market framework, a detailed analysis of the regulatory and market framework is needed to confirm the benefits and identify potential deployment barriers in each system's context. Under the current UK Renewable Heat Incentive, for example, hybrid HP-B systems only benefit from the feed-in tariff when operating with HP so this provides a disincentive to operate the gas boiler even if it could support the UK power system.

4.5. Further research requirements

In addition to assessing the system-wide value of hybrid heaters, the findings in this study should also motivate further research on modelling the system benefits of hybrid heaters, business models, market interaction and behavioural studies. Quantifying the risk mitigation potential of the operational flexibility to shift between fuels and the investment flexibility to upgrade a single fuel system into a hybrid could be valuable.

A unit commitment model could complement this investment model and further improve the operational cost analysis by including start-up costs of thermal power plants and wind uncertainty. Taking into account ancillary services could also increase the benefits of hybrid systems for the power system.

Electricity interconnections were not included in this analysis to keep the study focused. For the Irish case study, a UK interconnector would probably reduce wind curtailment and decrease the amount of low-cost electricity available to the hybrid heaters, which would specifically impact the hybrid B-R benefits. The electrification of heat could significantly impact the distribution grid in certain places and an investment analysis for distribution grids may also be warranted.

More research is required to capture operational stochasticity due to demand and supply variations in investment models. The perfect foresight assumption impact certain results as the emulation of de-rated storage capacity illustrates. Due to the high computational burden associated with stochastic optimisation, such a model would be limited to fewer input parameters. Furthermore it could complement, but not replace, the methodology presented in this paper which has the advantage of enabling analysis a wide range of technical and policy scenarios.

The system investment costs of a large-scale roll-out of different heater systems in 400 000 houses were compared against each other in this paper. Installing different technologies in different clusters of houses that interact with each other could create some complementarities between clusters or technologies. A preliminary analysis for 400 000 homes divided into 5 house clusters, indicated that installing HP-B heaters in all houses still offers the least-cost system.

Considering that the lifetime of heating systems is 15–20 years, the results from this 2030 analysis do leave sufficient flexibility to replace the heat system another time before 2050 as further decarbonisation will be required towards 2050 to mitigate global climate change. The 2030 results therefore do not lock-in development towards full decarbonisation. The methodology at hand is flexible and allows the study of energy systems beyond 2030.

5. Conclusion

Hybrid heating systems equipped with smart controls enable strategic integration of the power, residential heat and gas sectors resulting in system-wide cost reductions and strategic benefits. For such technologies, this paper has presented a least-cost investment methodology that optimises the combined power-residential heat system, including thermal storage. The hourly time resolution over a full year captures the ability of hybrid heaters to switch demand from gas to electricity, or vice versa, while minimising capital and operational cost. The results confirm that the deployment of hybrid HP-B heaters not only leads to the least-cost system and, compared to B, reduces gas consumption and CO_2 emissions, but also reduces power generation and heater investment cost compared to HPs. Hybrid B-R heaters provide energy savings by minimising wind curtailment throughout the year, but tend to use also more carbon—intensive coal generation. Hybrid HP-R heaters mainly only reduce heater capital cost compared to HPs.

Smart power system integration of hybrid heaters should be considered by system planners, technology developers and demand response providers, as mature technology options to manage power system investments even with high shares of variable renewables and as tool to meet strategic societal benefits such as carbon emission reductions and security of supply improvements.

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Nomenclature

Indices

Htech	residential heat technology (B, HP, R)
i	heat end-use (water, space)
PTech	electricity generation technology (wind, coal, CCGT, OCGT, oil)
t	time step, hours of a year (1:8760)

Variables

C^{elec}	total power generation capacity [MW]
$C^{elec,\ new}$	new power generation capacity [MW]
C^{heat}	heat generation capacity [MW]
$C^{sto,i}$	storage tank capacity for *i* [l]
E^{elec}	power generation [MWh]
$E^{heat,\ i}$	heat generation for end-use *i* [MWh]
E^{heat}	total heat generation [Wh]
E^{sto}	storage state variable (MWh)
L^i	loading of heat storage for *i* during 1 time step (MWh)
U^i	unloading of heat storage for *i* during 1 time step (MWh)

Parameters

a^{elec}	annuity factor for electricity plant [%]
a^{heat}	annuity factor for heaters [%]
Av_{PTech}	availability of electricity generation technologies [h]
$C^{elec,existing}$	existing capacity [MW]
$c_{p,water}$	specific heat capacity of water [kJ/kg K]
$CCredit_{PTech}$	capacity credit of electricity generation technologies [%]
$CFac_{Wind}(t)$	hourly capacity factors for wind generation [%]
CF	carbon emission factor [$kgCO_2$/MWh]
CP	carbon price [€/$kgCO_2$]
$D^{elec,ref}(t)$	hourly reference electricity demand [MWh]

$D^{elec,total}(t)$ hourly electricity demand [MWh]
$D^{elec,4heat}(t)$ hourly electricity demand for electricity-driven heaters [MWh]
$D^{heat,i}(t)$ hourly final heat demand for i [MWh]
IC^{elec}_{PTech} specific investment cost for power plants [€/MW]
$IC^{heat,equip}$ specific investment cost for heater equipment [€/MW]
$IC^{heat,inst}$ investment cost for heater installation [€/unit]
IC^{sto} specific investment cost for storage [€/l]
$IC_{IT\&Com}$ capital cost for smart controls [€]
FP fuel price [€/MWh]
$OMFix^{elec}_{PTech}$ fixed O&M costs [€/MW/year]
$OMFix^{heat}_{HTech}$ fixed O&M costs [€/unit/year]
$OMVar^{elec}_{PTech}$ variable O&M costs [€/MWh]
n number of households [/]
$SNSP$ system non-synchronous penetration [%]
$RAMP^{MAX}_{PTech}$ maximum ramp up and down capability of electricity plants [MW]
r discount rate [%]
β economic lifetime [years]
γ stationary heat loss [%]
η efficiency of electricity or heat generators [%]
ρ density of water [kg/l]
ΔTemp temperature difference with ambience [K]

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