Technical Feasibility of Low Carbon Heating in Domestic Buildings

Cost Appendix to the Report for Scottish Government's Directorate for Energy & Climate Change

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1 Cost of low-carbon heating technologies

The cost of each considered low-carbon heating technology was calculated considering both capex and opex costs for the year 2020. Following cost components were included:

Capex:

- Heating system base cost (£)
- Additional costs (£)

Opex:

- Maintenance cost (£/year)
- Fuel cost (£/year)

The final cost of a technology was calculated as the sum of the capex components and the discounted opex components. The opex cost were levelised over the lifetime of the technology with a discount rate of 3.5%. Our assumptions and cost sources for all cost components are reported in sections 1.1 to 1.4.

1.1 Heating system base cost and maintenance cost

The **heating system base cost** includes both the cost of the main appliance and the cost of its installation, but it does not include the costs of additional components, such as hot water cylinders or radiators.

The values of heating system base cost utilised in this study are shown in Figure 1 to Figure 4, reporting costs for a range of installed heating capacities.

Technologies that are currently not largely widespread are expected to experience a reduction in cost of the main unit between 2020 and 2040, due to economies of scale. Costs for 2020 are represented with a solid line, while costs for 2040 are represented by a dashed line.

Note that the heating system base cost for all technologies depends on the heating capacity of the device. Costs are reported as a list of total costs in £ for discrete values of installed capacity within a range for the following technologies: gas boiler, oil boiler, solid biomass boiler, bioLPG boiler, bioliquid boiler, hydrogen boiler and biomethane grid injection. For all other technologies, costs are reported as a combination of a “fixed cost” (in £ per unit) with a marginal component of “variable cost” (in £ per kWth of heating capacity of the unit). These cost components are also reported in Table 1.

Annual **maintenance costs** considered in this study are reported in Figure 5. These are expected to be constant for devices of all capacities, with the exception of solid biomass boilers, for which the annual maintenance cost is assumed to be 14.5 £/kW.

All data sources for heating system base costs and maintenance costs are summarised in Table 2.

Figure 1: Heating system base cost – Heat pumps

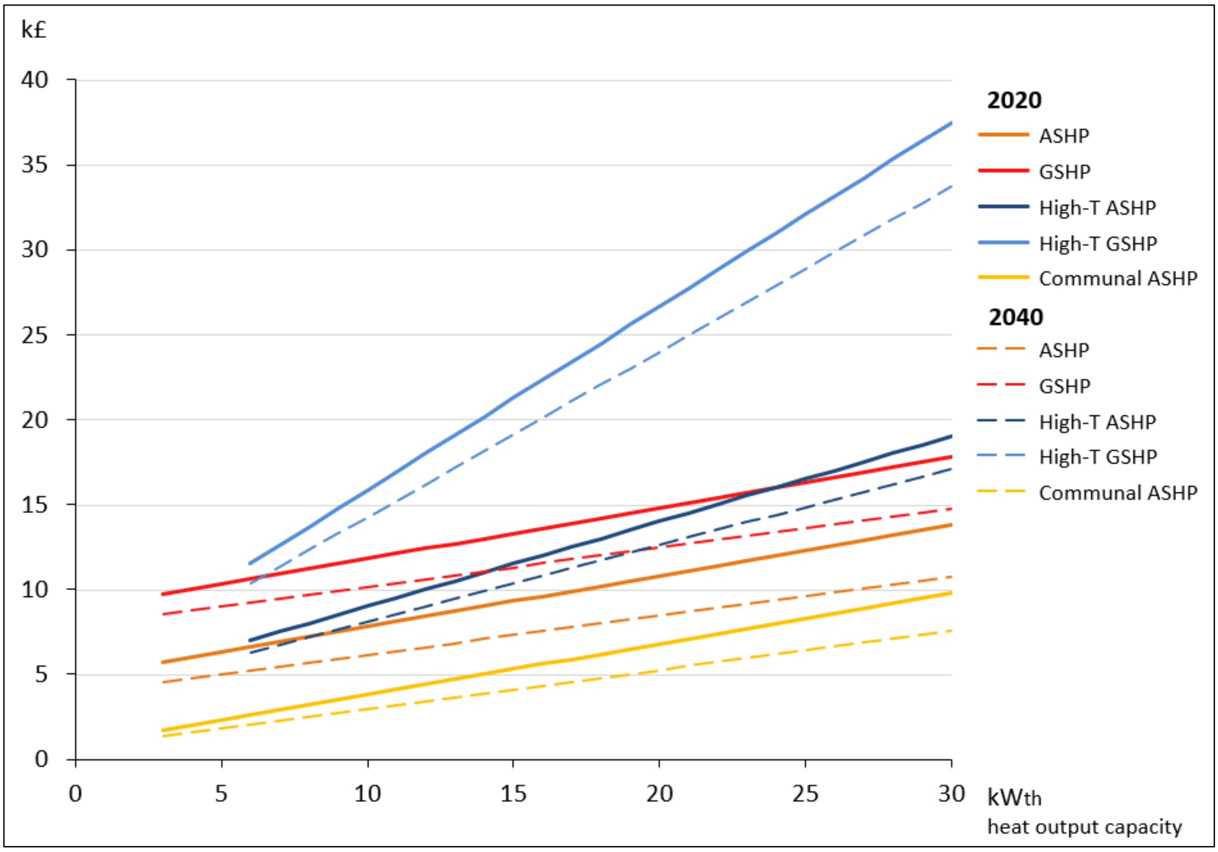


Figure 2: Heating system base cost – Electric heating and hybrid heat pumps

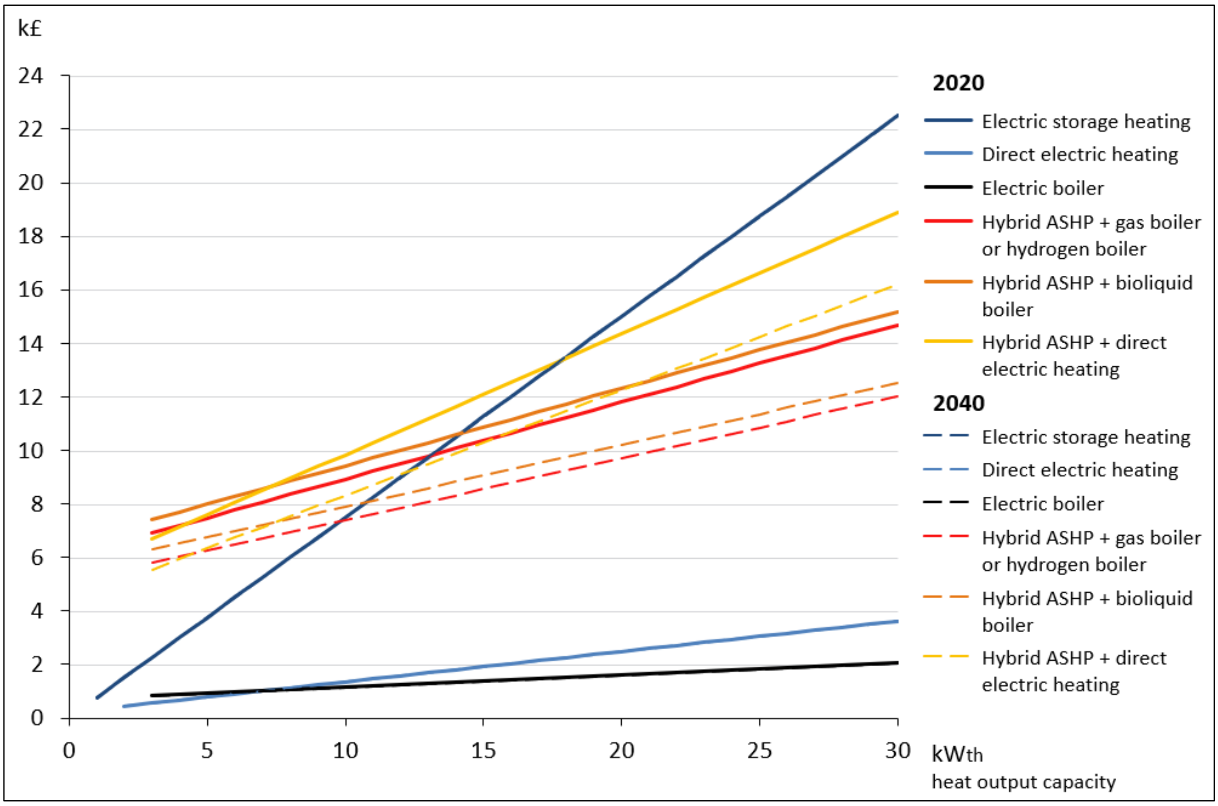


Figure 3: Heating system base cost – Bioenergy boilers and low carbon gas

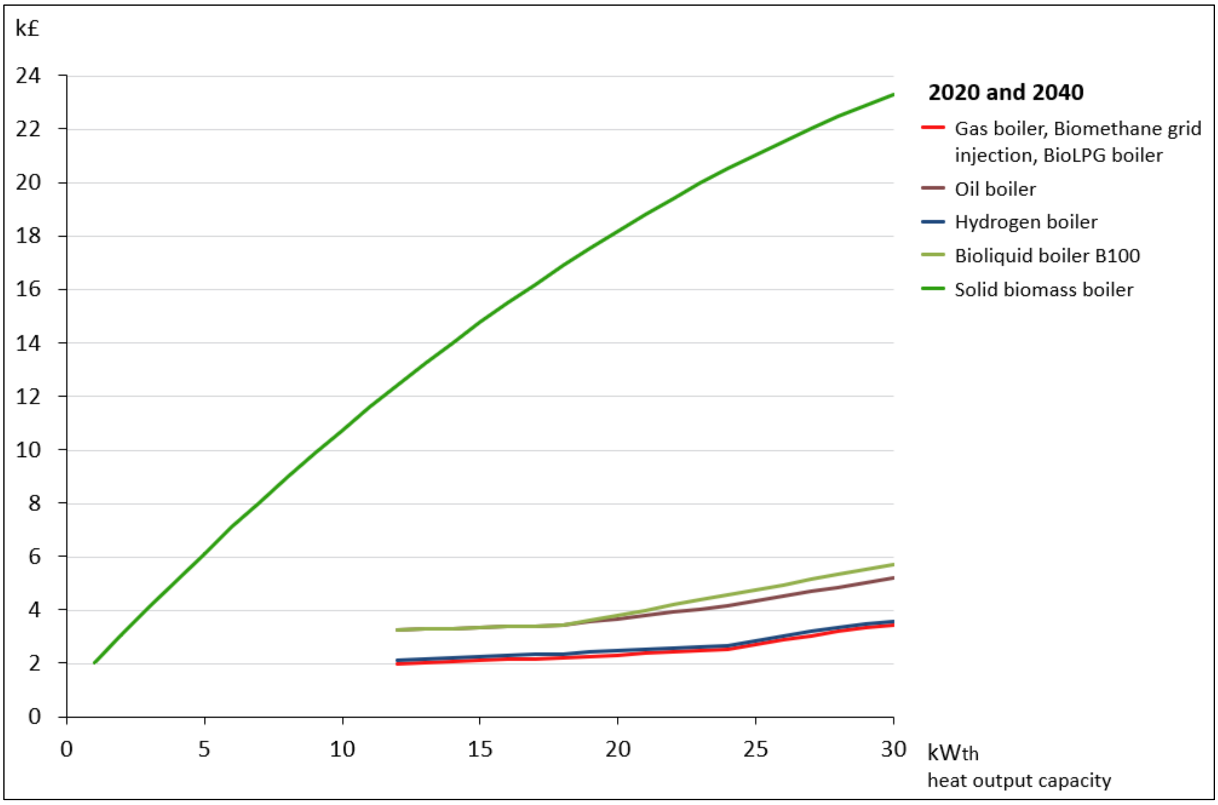


Figure 4: Heating system base cost – Combinations with solar thermal

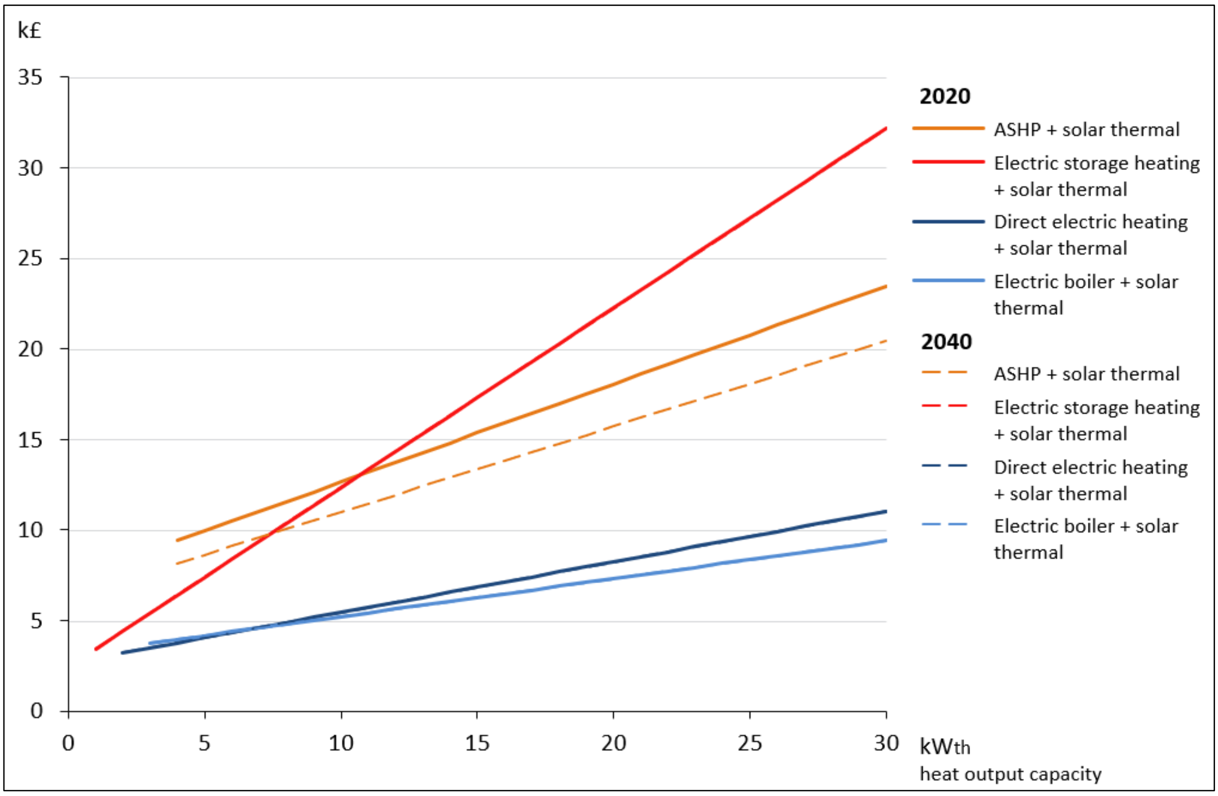
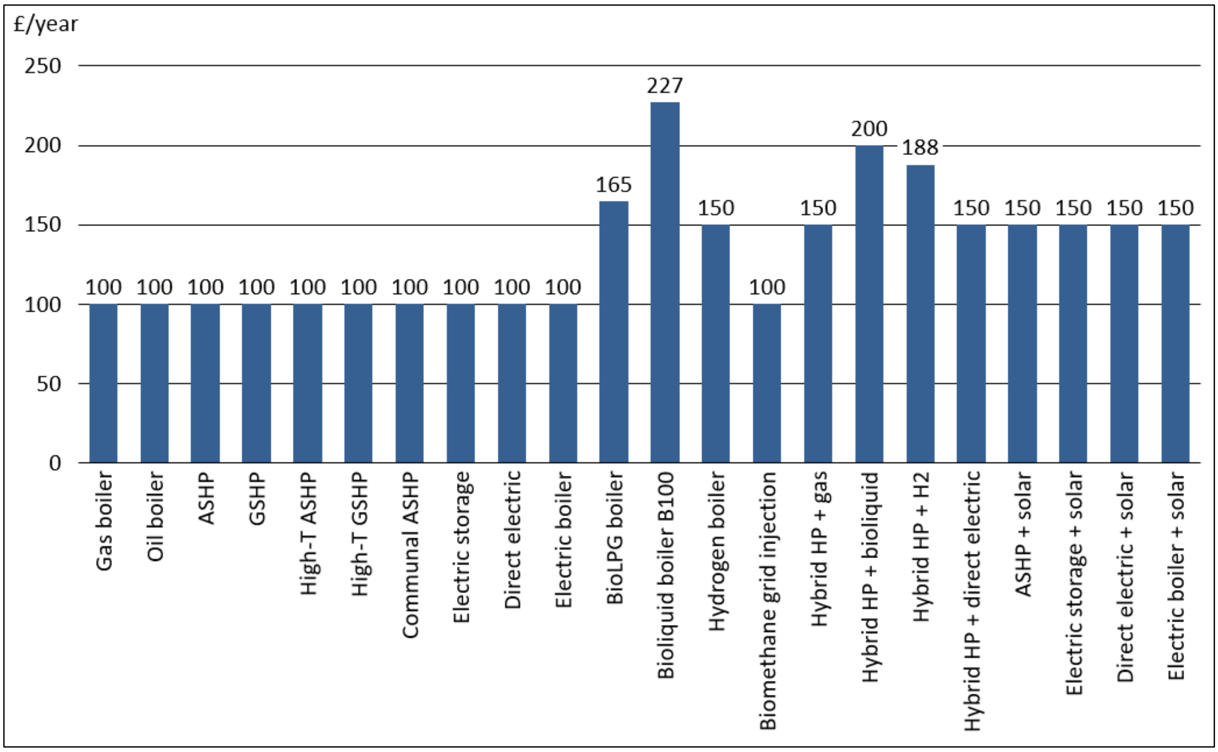


Table 1: Components of heating system base cost

	Fixed CAPEX (£)		Marginal CAPEX (£/kW$_{th}$)	
	2020	2040	2020	2040
ASHP	4,804	3,843	300	231
GSHP	8,804	7,843	300	231
High-T ASHP	4,000	3,600	500	450
High-T GSHP	5,000	4,500	1,083	975
Communal ASHP	801	641	300	231
Electric storage heating	-	-	750	750
Direct electric heating	227	227	113	113
Electric boiler	700	700	45	45
Hybrid ASHP + gas boiler or hydrogen boiler	6,042	5,093	288	231
Hybrid ASHP + bioliquid boiler	6,546	5,597	288	231
Hybrid ASHP + direct electric heating	5,319	4,370	452	395
ASHP + solar	7,229	6,268	541	472
Electric storage + solar	2,425	2,425	992	992
Electric resistive + solar	2,652	2,652	279	279
Electric boiler + solar	3,121	3,121	209	209

Figure 5: Annual maintenance cost



Annual maintenance costs for solid biomass boilers were assumed to depend on the capacity of the appliance and to amount to 14.5 £/kW$_{th}$.

Table 2: Sources and assumptions on low-carbon heating technology costs

Technology	Sources	Assumptions
Gas boiler	As Fifth Carbon Budget, converted to 2020 prices.	
Oil boiler	As Fifth Carbon Budget, converted to 2020 prices.	
ASHP	2020 values from Hybrid Heat Pumps (2017), Element Energy for BEIS	Reduction in cost of unit and installation of 20% between 2020 and 2040.
GSHP	2020 values from Hybrid Heat Pumps (2017), Element Energy for BEIS	Reduction in cost of unit and installation of 20% between 2020 and 2040. Assuming ground loop shared between two properties.
High-T ASHP	2020 values from Evidence gathering - Domestic High Temperature Heat Pumps (2016), BEIS	Reduction in cost of unit and installation of 10% between 2020 and 2040.
High-T GSHP	2020 values from Evidence gathering - Domestic High Temperature Heat Pumps (2016), BEIS	Reduction in cost of unit and installation of 10% between 2020 and 2040. Assuming ground loop shared between two properties.
Communal ASHP	6 homes used as the size of the communal heating system based on the average terrace length from HCLG English Housing Survey 2017-2018	Assumes a communal HP serving 6 homes. Fixed and marginal capex and same as for individual ASHP and shared across the 6 homes.
Electric storage	From Evidence gathering for electric heating options in off gas grid homes (2019), Element Energy for BEIS	Capex constant for all years, as established technology.
Electric resistive	From Evidence gathering for electric heating options in off gas grid homes (2019), Element Energy for BEIS	Capex constant for all years, as established technology. Opex same as for electric storage.
Electric boiler	From Evidence gathering for electric heating options in off gas grid homes (2019), Element Energy for BEIS	Capex constant for all years, as established technology. Opex same as for gas boilers and electric storage
Solid biomass boiler	Capex from Fifth Carbon Budget dataset converted to 2020 prices. Opex from NERA 2009: The UK Supply Curve for Renewable Heat	
BioLPG boiler	Capex of unit and installation from ClimateXChange 2019, The potential contribution of bioenergy to Scotland's energy system.	Opex same as for gas boiler with additional cost for the delivery and storage of bioLPG

	Additional opex for the delivery and storage of gas based on LPG Gas Central Heating Costs, Household Quotes 2018.	
Bioliquid boiler B100	ClimateXChange 2019, The potential contribution of bioenergy to Scotland's energy system. NNFCC 2019, Heating Options for Off-Gas Grid Consumers. BoilerGuide New Oil Boiler Replacement – Installation Costs (accessed 04/10/2019).	Dedicated bioliquid installation. Fixed opex assumed to be the same as for general boilers, plus oil tank costs. Oil tank can be rented or owned. Cost of tank rental or cost of own tank assumed to be equivalent and included in opex. Oil tank cost with installation £1,900 (over 15 yr)
Hydrogen boiler	Hydrogen supply chain evidence base (2018), Element Energy for BEIS	£153 added to cost of gas boiler to account for increased cost of Hydrogen boiler (Hydrogen-only boiler and Hyready boiler). Uplift of 50% in the opex compared to gas boiler due to the need to replace catalyst used to reduce NOx emissions (for both Hydrogen-only boiler and Hyready boiler).
Biomethane grid injection		Same appliance as gas boiler
Hybrid HP + gas	2020 values from Hybrid Heat Pumps (2017), Element Energy for BEIS. Increase in capex for Hyready boiler and uplift in opex for catalyst replacement in line with Hydrogen supply chain evidence base (2018), Element Energy for BEIS	Hyready boiler in gas mode. Reduction in cost of heat pump unit of 20% between 2020 and 2040. Opex assumed to be £50 lower than the sum of the opex for the two components of the hybrid system (£100 each) due to economies of scale.
Hybrid HP + bioliquid	2020 values from Hybrid Heat Pumps (2017), Element Energy for BEIS. NNFCC 2019, Heating Options for Off-Gas Grid Consumers. BoilerGuide New Oil Boiler Replacement – Installation Costs (accessed 04/10/2019).	Reduction in cost of heat pump unit of 20% between 2020 and 2040. Opex assumed to be £50 lower than the sum of the opex for the two components of the hybrid system due to economies of scale. Additional OPEX £50 for small oil tank (£750 over 15 yr).
Hybrid HP + H2	2020 values from Hybrid Heat Pumps (2017), Element Energy for BEIS Increase in capex for Hyready boiler and uplift in opex for catalyst replacement in line with Hydrogen supply chain evidence base (2018), Element Energy for BEIS	Hyready boiler in hydrogen mode. Reduction in cost of heat pump unit of 20% between 2020 and 2040. Opex assumed to be £50 lower than the sum of the opex for the two components of the hybrid system due to economies of scale; uplift of 50% in the component of the opex associated with the hydrogen boiler due to replacement of the catalyst

		used to reduce NOx emissions when operating in hydrogen mode.
Hybrid HP + resistive		Capex derived by removing boiler component of hybrid heat pump and adding cost of resistive heating based on modelled kW. Opex assumed to be £50 lower than the sum of the opex for the two components of the hybrid system due to economies of scale.
Combinations with solar thermal	Costs as Fifth Carbon Budget, converted to 2020 prices. Heat delivered assumption based on NERA 2009: The UK Supply Curve for Renewable Heat, table B.13	Heat delivered by solar collectors calculated assuming that solar thermal delivers no more than 60% of hot water demand or 643 kWh/kW, whichever is lower. Opex assumed to be £50 lower than the sum of the opex for the two components of the hybrid system due to economies of scale.

1.2 Technology efficiency and fuel use

All assumptions around lifetime, load factor, fuel type, heating efficiency and the portion of supplied space heating and hot water are reported in Table 3. The load factor was utilised to calculate peak heating demand from the annual heating demand. Heating efficiency refers to the higher heating value for combustion-based technologies.

Heating efficiency of heat pump technologies varies depending on the flow temperature at which space heating and hot water are delivered and is reported in Table 4. The efficiency of a heat pump is expressed as the seasonal performance factor (SPF), defined as the ratio of the supplied heat to the total electrical energy demand over one year. The combined SPF, utilised to calculate electricity consumption, includes the delivery of heat for both space heating and for hot water production, assuming the ratio between space heating and hot water production is 3.5:1. The hot water SPF is assumed to be the same as the space heating SPF when operating with flow temperature of 60°C.

Table 3: Assumptions on lifetime, load factor, fuel use and heating efficiency

Technology	Lifetime	Load factor	Fuel	Heating efficiency	% space heating demand	% hot water demand
ASHP	18	16%	Electricity - Peak	Table 4	100%	100%
GSHP	22.5	16%	Electricity - Peak	Table 4	100%	100%
High-T ASHP	18	16%	Electricity - Peak	Table 4	100%	100%
High-T GSHP	22.5	16%	Electricity - Peak	Table 4	100%	100%

Technology	Lifetime	Load factor	Fuel	Heating efficiency	% space heating demand	% hot water demand
Communal ASHP	18	16%	Electricity - Peak	Table 4	100%	100%
Electric storage	15	16%	Electricity - Off peak	100%	100%	100%
Electric resistive	15	11%	Electricity - Peak	100%	100%	100%
Electric boiler	15	7%	Electricity - Peak	100%	100%	100%
Solid biomass boiler	15	16%	Biomass	74%	100%	100%
BioLPG boiler	15	7%	BioLPG	87%	100%	100%
Bioliquid boiler B100	15	7%	Bioliquid	84%	100%	100%
Hydrogen boiler	15	7%	Hydrogen	87%	100%	100%
Biomethane grid injection	15	7%	Biomethane	87%	100%	100%
Hybrid HP + gas boiler	15	25%	Electricity - Peak	Table 4	80%	0%
			Gas	87%	20%	100%
Hybrid HP + gas boiler, with hot water cylinder	15	25%	Electricity - Peak	Table 4	80%	80%
			Gas	87%	20%	20%
Hybrid HP + bioliquid boiler	15	25%	Electricity - Peak	Table 4	80%	0%
			Bioliquid	84%	20%	100%
Hybrid HP + bioliquid boiler, with hot water cylinder	15	25%	Electricity - Peak	Table 4	80%	80%
			Bioliquid	84%	20%	20%
Hybrid HP + hydrogen boiler	15	25%	Electricity - Peak	Table 4	80%	0%
			Hydrogen	87%	20%	100%
Hybrid HP + hydrogen boiler, with hot water cylinder	15	25%	Electricity - Peak	Table 4	80%	80%
			Hydrogen	87%	20%	20%
Hybrid HP + direct electric heating	15	25%	Electricity - Peak	Table 4	80%	0%
			Electricity - Peak	100%	20%	100%

Technology	Lifetime	Load factor	Fuel	Heating efficiency	% space heating demand	% hot water demand
Hybrid HP + direct electric heating, with hot water cylinder	15	25%	Electricity - Peak	Table 4	80%	80%
			Electricity - Peak	100%	20%	20%
DH	15	7%	Heat from DH	100%	100%	100%
Combinations with solar	18	N/A	Solar	N/A	0%	60%
Gas boiler	15	7%	Gas	87%	100%	100%
Oil boiler	15	7%	Oil	84%	100%	100%

Table 4: Heating efficiency of heat pump technologies

Technology	Flow Temperature (°C)	Space heating SPF		Combined SPF	
		2020	2040	2020	2040
ASHP	35	3.60	4.06	3.12	3.62
	40	3.40	3.87	3.00	3.50
	45	3.00	3.48	2.75	3.25
	50	2.70	3.19	2.54	3.04
	55	2.40	2.90	2.33	2.83
	60	2.10	2.60	2.10	2.60
GSHP	35	3.77	4.31	3.51	3.96
	40	3.59	4.07	3.38	3.8
	45	3.40	3.84	3.25	3.64
	50	3.21	3.60	3.11	3.47
	55	3.02	3.35	2.97	3.29
	60	2.83	3.09	2.83	3.09
Communal ASHP	35	3.60	4.06	3.12	3.62
	40	3.40	3.87	3.00	3.50
	45	3.00	3.48	2.75	3.25
	50	2.70	3.19	2.54	3.04
	55	2.40	2.90	2.33	2.83
	60	2.10	2.60	2.10	2.60
High-T ASHP and GSHP	75	2.95	3.00	2.95	3.00

An improvement of 0.5 in the combined SPF at flow temperature of 60°C is assumed between 2020 and 2030, in line with assumption of the 5th Carbon Budget Advice analysis by the CCC[1].

[1] Element Energy & UCL (2019), Analysis on abating direct emissions from 'hard-to-decarbonise' homes

The flow temperature of the system was assigned to each archetype by choosing the lowest flow temperature suitable to meet the specific heat demand, as reported in Table 5.

Table 5: Flow temperature of heat pumps depending on the archetype's specific heat demand

Specific heat demand (W/m^2)	Flow Temperature (°C)
< 80	35
80 - 100	40
100 - 120	45
120 - 150	50
> 150	unsuitable

1.3 Additional costs

Additional costs considered in this study include costs for the installation of additional components required by the new low-carbon heating system (e.g. hot water cylinder or low-temperature radiators) but also costs for the removal of components of the old heating system that are no longer required (e.g. boiler decommissioning) and costs for equipment not linked to the heating system (e.g. replacement of cooker/hob when moving to a non-gas based heating technology).

A list of the additional costs related to equipment and measures is reported in Table 6. The applicability of these costs will depend both on the new heating technology that is being installed and on the counterfactual heating technology which is being decommissioned. In fact, some of the additional components of the counterfactual heating system may be utilised for the new heating system. Table 7 and Table 8 show an overview of how these costs were applied.

Table 6: Additional cost components

Equipment / measure	Fixed capex (£)	Marginal capex	Source	Assumptions
Hot water cylinder	1,059	-	Evidence gathering for electric heating options in off gas grid homes (2019), Element Energy for BEIS	180L storage volume
Additional thermal store to allow some use of Off-peak electricity	1,711	-	Evidence gathering for electric heating options in off gas grid homes (2019), Element Energy for BEIS	Two 180L hot water cylinders with shared installation cost
Point-of-use hot water systems	2,060	-	Evidence gathering for electric heating options in off gas grid homes (2019),	Typical installation of 3 electric taps and 1 electric shower per dwelling

Equipment / measure	Fixed capex (£)	Marginal capex	Source	Assumptions
			Element Energy for BEIS	
Conversion to low T radiators	1,100 to 2,567	-	Hybrid Heat Pumps (2017), Element Energy for BEIS	Applied in dwellings with existing wet heating system. Depending on building size.
Replacement of cooker/hob	315	-	Analysis of Alternative UK Heat Decarbonisation Pathways (2018), Imperial College for CCC	Weighted average across gas households, based on cost of £500 (2017 prices), 23.9m gas households, with 14.8m gas hobs and 8.4m gas ovens.
Installation of wet distribution system	1,273	5 £/m^2	Evidence gathering for electric heating options in off gas grid homes (2019), Element Energy for BEIS	Only applied in dwellings with electric system
Removal of wet heating system	204		Evidence gathering for electric heating options in off gas grid homes (2019), Element Energy for BEIS	Only applied in dwellings with non-electric system
Decommissioning of boiler	509		Analysis of Alternative UK Heat Decarbonisation Pathways (2018), Imperial College for CCC	Includes decommissioning of other non-cooking gas appliances
H_2 conversion costs - hydrogen boiler, hydrogen hybrid HP	560		Hydrogen supply chain evidence base (2018), Element Energy for BEIS	£509 for pipework and £51 added as labour cost for the switchover of the Hyready boiler from gas to H2.
Additional pipework for communal ASHP in flat	3,364	-	Element Energy modelling for private sector client (2018)	Excluding internal emitter replacement. Includes heat exchange unit and meter. 2.5m service pipe per flat, 10m lateral pipe and 3.1m heat riser per floor, pump, installation and labour.

Equipment / measure	Fixed capex (£)	Marginal capex	Source	Assumptions
Additional pipework for communal HP in terrace house	6,157	-	Element Energy modelling for private sector client (2018)	Excluding internal emitter replacement. Includes heat exchange unit and meter. 30m external pipeline per communal heating system and 2.5m service pipe per house.
Wiring for direct electric heating	89	135 £/kW	Evidence gathering for electric heating options in off gas grid homes (2019), Element Energy for BEIS	Only applied in dwellings with non-electric heating when switching to electric heating
Wiring for storage heating	509	178 £/kW	Evidence gathering for electric heating options in off gas grid homes (2019), Element Energy for BEIS	Applied in dwellings with non-storage heating when switching to storage heating

Table 7: Application of additional costs (1/2)

New system	Existing system	Removal of wet system	Installation of wet system	Communal heating pipework and	Storage heating electrical wiring	Resistive heating electrical wiring	Hot water tank
ASHP GSHP ASHP + solar thermal	Gas	N	N	N	N	N	Y
	Oil	N	N	N	N	N	Y
	Electric	N	Y	N	N	N	N
High-T ASHP High-T GSHP	Gas	N	N	N	N	N	N
	Oil	N	N	N	N	N	N
	Electric	N	Y	N	N	N	N
Communal ASHP	Gas	N	N	Y	N	N	Y
	Oil	N	N	Y	N	N	Y
	Electric	N	Y	Y	N	N	N
Electric storage Electric storage + solar	Gas	Y	N	N	Y	N	Y
	Oil	Y	N	N	Y	N	Y
	Electric	N	N	N	[1]	N	N
Electric resistive Electric resistive + solar	Gas	Y	N	N	N	Y	Y
	Oil	Y	N	N	N	Y	Y
	Electric	N	N	N	N	N	N
Electric boiler Electric boiler + solar	Gas	N	N	N	N	N	N
	Oil	N	N	N	N	N	N
	Electric	N	Y	N	N	N	N
Solid biomass boiler	Gas	N	N	N	N	N	N
	Oil	N	N	N	N	N	N
	Electric	N	Y	N	N	N	N
BioLPG boiler	Gas	N	N	N	N	N	N
	Oil	N	N	N	N	N	N
	Electric	N	Y	N	N	N	N
Bioliquid boiler B100	Gas	N	N	N	N	N	N
	Oil	N	N	N	N	N	N
	Electric	N	Y	N	N	N	N
Hydrogen boiler	Gas	N	N	N	N	N	N
	Oil	N	N	N	N	N	N
	Electric	N	Y	N	N	N	N
Biomethane grid injection	Gas	N	N	N	N	N	N
	Oil	N	N	N	N	N	N
	Electric	N	Y	N	N	N	N
Hybrid HP + gas	Gas	N	N	N	N	N	N
	Oil	N	N	N	N	N	N
	Electric	N	Y	N	N	N	N
Hybrid HP + gas, with hot water cylinder	Gas	N	N	N	N	N	[2]
	Oil	N	N	N	N	N	[2]
	Electric	N	Y	N	N	N	N
Hybrid HP + bioliquid	Gas	N	N	N	N	N	N
	Oil	N	N	N	N	N	N
	Electric	N	Y	N	N	N	N
Hybrid HP + bioliquid, with hot water cylinder	Gas	N	N	N	N	N	[2]
	Oil	N	N	N	N	N	[2]

New system	Existing system	Removal of wet system	Installation of wet system	Communal heating pipework and	Storage heating electrical wiring	Resistive heating electrical wiring	Hot water tank
	Electric	N	Y	N	N	N	N
Hybrid HP + hydrogen	Gas	N	N	N	N	N	N
	Oil	N	N	N	N	N	N
	Electric	N	Y	N	N	N	N
Hybrid HP + hydrogen, with hot water cylinder	Gas	N	N	N	N	N	[2]
	Oil	N	N	N	N	N	[2]
	Electric	N	Y	N	N	N	N
Hybrid HP + direct electric	Gas	N	N	N	N	N	N
	Oil	N	N	N	N	N	N
	Electric	N	Y	N	N	N	N
Hybrid HP + direct electric, with hot water cylinder	Gas	N	N	N	N	N	[2]
	Oil	N	N	N	N	N	[2]
	Electric	N	Y	N	N	N	N
District heating	Gas	N	N	N	N	N	N
	Oil	N	N	N	N	N	N
	Electric	N	Y	N	N	N	N

Legend:

Y	Applies for all dwellings
[…]	Applies for some dwellings. See numbers below.
N	Does not apply for any dwellings

[1] Only applies if the counterfactual technology is direct electric heating

[2] Only applicable where the heat pump is meeting the hot water demand. Where the boiler is meeting hot water demand then on-demand hot water from a combi boiler is assumed.

Table 8: Application of additional costs (2/2)

New system	Existing system	Point of use DHW	Radiator upgrades	Decommission boiler and non-cooking gas	Decommission / replace cooking appliances	Installation of liquid fuel tank	Hydrogen pipework and conversion
ASHP GSHP ASHP + solar thermal	Gas	N	[4]	Y	[6]	N	N
	Oil	N	[4]	Y	N	N	N
	Electric	N	[4]	N	N	N	N
High-T ASHP High-T GSHP	Gas	N	N	Y	[6]	N	N
	Oil	N	N	Y	N	N	N
	Electric	N	N	N	N	N	N
Communal ASHP	Gas	N	[4]	Y	[6]	N	N
	Oil	N	[4]	Y	N	N	N
	Electric	N	[4]	N	N	N	N
Electric storage Electric storage + solar thermal	Gas	[3]	N	Y	[6]	N	N
	Oil	[3]	N	Y	N	N	N
	Electric	N	N	N	N	N	N
Electric resistive Electric resistive + solar thermal	Gas	[3]	N	Y	[6]	N	N
	Oil	[3]	N	Y	N	N	N
	Electric	N	N	N	N	N	N
Electric boiler Electric boiler + solar thermal	Gas	N	N	Y	[6]	N	N
	Oil	N	N	Y	N	N	N
	Electric	N	N	N	N	N	N
Solid biomass boiler	Gas	N	N	[5]	[6]	N	N
	Oil	N	N	Y	N	N	N
	Electric	N	N	N	N	N	N
BioLPG boiler	Gas	N	N	N	[6]	N	N
	Oil	N	N	Y	N	N	N
	Electric	N	N	N	N	N	N
Bioliquid boiler B100	Gas	N	N	Y	[6]	Y	N
	Oil	N	N	Y	N	Y	N
	Electric	N	N	N	N	Y	N
Hydrogen boiler	Gas	N	N	N	[6]	N	Y
	Oil	N	N	Y	N	N	Y
	Electric	N	N	N	N	N	Y
Biomethane grid injection	Gas	N	N	N	N	N	N
	Oil	N	N	Y	N	N	N
	Electric	N	N	N	N	N	N
Hybrid HP + gas	Gas	[3]	N	N	N	N	N
	Oil	[3]	N	Y	N	N	N
	Electric	N	N	N	N	N	N
Hybrid HP + gas, with hot water cylinder	Gas	N	N	N	N	N	N
	Oil	N	N	Y	N	N	N
	Electric	N	N	N	N	N	N
Hybrid HP + bioliquid	Gas	[3]	N	Y	[6]	Y	N
	Oil	[3]	N	Y	N	Y	N

New system	Existing system	Point of use DHW	Radiator upgrades	Decommission boiler and non-cooking gas	Decommission / replace cooking appliances	Installation of liquid fuel tank	Hydrogen pipework and conversion
	Electric	N	N	N	N	Y	N
Hybrid HP + bioliquid, with hot water cylinder	Gas	N	N	N	[6]	Y	N
	Oil	N	N	Y	N	Y	N
	Electric	N	N	N	N	Y	N
Hybrid HP + hydrogen	Gas	[3]	N	N	[6]	N	Y
	Oil	[3]	N	Y	N	N	Y
	Electric	N	N	N	N	N	Y
Hybrid HP + hydrogen, with hot water cylinder	Gas	N	N	N	[6]	N	Y
	Oil	N	N	Y	N	N	Y
	Electric	N	N	N	N	N	Y
Hybrid HP + direct electric	Gas	[3]	N	Y	[6]	N	N
	Oil	[3]	N	Y	N	N	N
	Electric	N	N	N	N	N	N
Hybrid HP + direct electric, with hot water cylinder	Gas	N	N	N	[6]	N	N
	Oil	N	N	Y	N	N	N
	Electric	N	N	N	N	N	N
District heating	Gas	N	[4]	Y	[6]	N	N
	Oil	N	[4]	Y	N	N	N
	Electric	N	[4]	N	N	N	N

Legend:

Y	Applies for all dwellings
[…]	Applies for some dwellings. See numbers below.
N	Does not apply for any dwellings

[3] Point-of-use hot water system is an option to provide on-demand hot water where a combi boiler is not available/used to provide hot water in space constrained homes. This is therefore applied in space-constrained homes assumed not to have a hot water cylinder (assumed to be the case here in all homes where the existing system is a boiler) in the following cases: (i) alongside electric resistive or electric storage heating; (ii) alongside hybrid heat pump + resistive heating (not alongside any other types of hybrid heat pump).

[4] Applied when standard radiators are deemed to be insufficient to supply peak heat demand, based on an assumed oversizing factor for standard radiators of 1.3: if (1.3 x baseline space heating demand) divided by (required oversize factor x energy demand after energy efficiency) is less than 1 then radiator upgrades are required. The required oversize factor is determined by the flow temperature of the system.

[5] Cost is applied in the model, but suitability assumptions do not allow biomass boilers in on-gas homes therefore this cost is not applied in practice

[6] Assume that 62% of gas households have a gas hob and 35% have a gas oven; a weighted average cost is applied to all gas households assuming £500 conversion cost for either hob, oven, or hob and oven replacement, and assuming all households with a gas oven also have a gas hob.

1.4 Fuel cost

Fuel costs considered in this study for the period between 2020 and 2050 are shown in Figure 6 and Figure 7. Data sources and assumptions behind the cost of fuels and grid electricity are summarised in Table 9. The methodology and assumptions around the cost of hydrogen are reported in section 1.4.1.

Figure 6: Cost of fuels and grid electricity

Figure 7: Cost of hydrogen

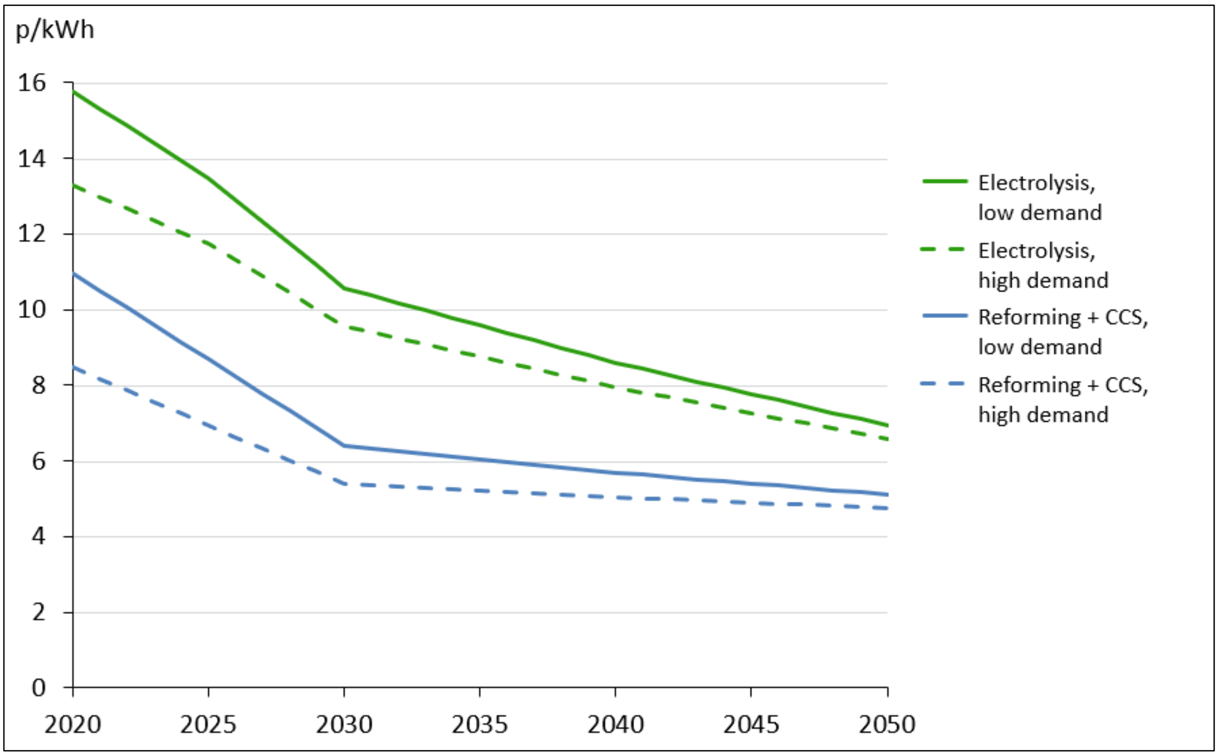


Table 9: Sources and assumptions on the cost of fuels and grid electricity

Fuel type	Sources	Assumptions
Electricity (Standard, Off Peak, On Peak)	Projections from BEIS Green Book data tables, Long-run variable costs of energy supply (LRVCs): Electricity LRVC – Central, Domestic. Off peak cost = 60% on-peak cost from Evidence gathering for electric heating options in off gas grid homes (2019), Element Energy for BEIS	"Electricity - Standard" composed of 70% on-peak and 30% off-peak
Heat from DH	Cost calculated from modelling results based on District heating and local approaches to heat decarbonisation (2015) Element Energy for CCC 2015	
LPG (bottled gas)	Costs based on ratio of annual retail cost of LPG compared to natural gas from Biopropane for the off-grid sector (2016) EUA	
BioLPG	Costs based on ratio of annual retail cost of biopropane to natural gas from Biopropane for the off-grid sector (2016) EUA	
Biomethane	Costs based on ratio of annual retail cost of biomethane to natural gas. For large scale production, cost of biomethane: USD 0.65/LGE = 7.36 $c/kWh (from IRENA, Biomethane), natural gas price of 4.3 $c/kWh (from Oxford Institute for Energy Studies 2017, Biogas: A significant contribution to decarbonising gas markets?). Cost assumed to remain constant over time (from IRENA 2013, New fuels for transport: the cost of renewable solutions).	Assuming large scale production of biomethane. Cost of biomethane assumed to be 70% higher than natural gas in 2018.
Bioliquid 100	Costs based on ratio of annual retail cost of bioliquid B100 to diesel. Proportion of cost of Bioliquid B100 and of diesel from DOA alternative fuel price report (from US DOA, Alternative Fuel Price Report).	Cost of Bioliquid B100 25% higher than for diesel in 2018. Cost assumed to remain constant over time from 2020.
Gas	Projections from BEIS Green Book data tables, Long-run variable costs of energy supply (LRVCs): Gas LRVC – Central, Domestic	
Oil	CCC's long-term targets analysis (2019)	

1.4.1 Hydrogen cost

While the cost of hydrogen predominantly depends on the chosen type of production technology and on the year of demand, additional costs for repurposing the current gas network to operation with hydrogen must also be considered. Additional costs considered in this study include the cost of upgrading the gas distribution and transmission networks, as well as the creation of hydrogen interseasonal storage in large salt caverns, as reported in Table 10.

Table 10: Gas network repurposing, cost components

	Capex (£bn)	Opex (£bn/yr)
Distribution grid repurposing[2]	22.2	0
Hydrogen transmission network[3]	4.9	0.28
Hydrogen storage[3]	6.5	0.39

The cost of the infrastructure upgrade is assumed to be levelised over a period of 30 years with a discount rate of 3.5%. The deployment of the grid upgrades and of the storage capacity is expected to occur gradually, achieving 10% of completion in 2020, 75% by 2030 and 100% by 2040, such that only the capex of the completed portion is incurred.

The network upgrade cost per kWh of hydrogen produced was finally estimated for a high-demand and a low-demand scenario. The values of high hydrogen demand are based on the "Full Hydrogen" scenario utilised in the recent report on hydrogen in the UK by the CCC, considering repurposed gas networks and widespread hydrogen availability, with heating delivered by hydrogen boilers[4]. The values utilised for low hydrogen demand consider a less intensive utilisation of hydrogen, leading to roughly half the demand of the "Full Hydrogen" scenario.

Deployment rates, assumptions on hydrogen demand between 2020 to 2050, as well as total discounted upgrade costs per kWh H2 are reported in Table 11.

Table 11: Gas network repurposing, deployment and total cost

	Unit	2020	2030	2040	2050
Deployment of upgrades and H_2 storage	%	10%	75%	100%	100%
Capex	£bn	3.4	25.2	33.6	33.6
Opex	£bn/yr	0.67	0.67	0.67	0.67
Hydrogen demand (high)	TWh/r	21	203	385	704
Hydrogen demand (low)	TWh/r	13	101	192	352
Network upgrade cost (high H_2 demand)	p/kWh H_2	4.1	1.0	0.6	0.4
Network upgrade cost (low H_2 demand)	p/kWh H_2	6.6	2.0	1.3	0.7

Two main types of technologies for the production of low-carbon hydrogen were considered in this study: reforming with CCS and electrolysis.

[2] Element Energy for BEIS 2018, Hydrogen supply chain: evidence base
[3] Element Energy for NIC 2018, Cost analysis of future heat infrastructure
[4] CCC 2018, Hydrogen in a low-carbon economy

Steam Methane Reforming (SMR) is currently the most common reforming technology employed for hydrogen production. While Advanced Reforming with CCS has the potential to offer a higher capture rate than SMR with CCS, this technology is expected to be deployed at commercial scale at a later date. In this study it was assumed that low-carbon reformed hydrogen is produced exclusively via SMR + CCS until 2030, after which the portion of hydrogen produced with advanced reforming + CCS will increase, reaching 50% of production in 2040 and 100% in 2050.

The most mature technology for the production of electrolysed hydrogen are alkaline electrolysers, currently producing the vast majority of electrolysed hydrogen worldwide. A minor portion of global hydrogen is produced with Proton Exchange Membranes (PEM), a cheaper technology which is currently at the demonstration stage[5]. In this study it was assumed that alkaline electrolysers dominate the production of electrolysed hydrogen until 2025, after which PEM electrolysers are introduced at scale, reaching 100% of electrolysed hydrogen production by 2040. All fuel production cost assumptions are reported in Table 12.

Table 12: Cost of hydrogen production

	Unit	2020	2030	2040	2050
Reforming + CCS[5]	p/kWh	4.4	4.4	4.4	4.4
Electrolysis[5]	p/kWh	9.2	8.6	7.3	6.2

Figure 7 reports the cost of hydrogen including both production and levelised cost of network repurposing. Cost estimates are produced for both reforming and electrolysis technologies in case of both high and low hydrogen demand.

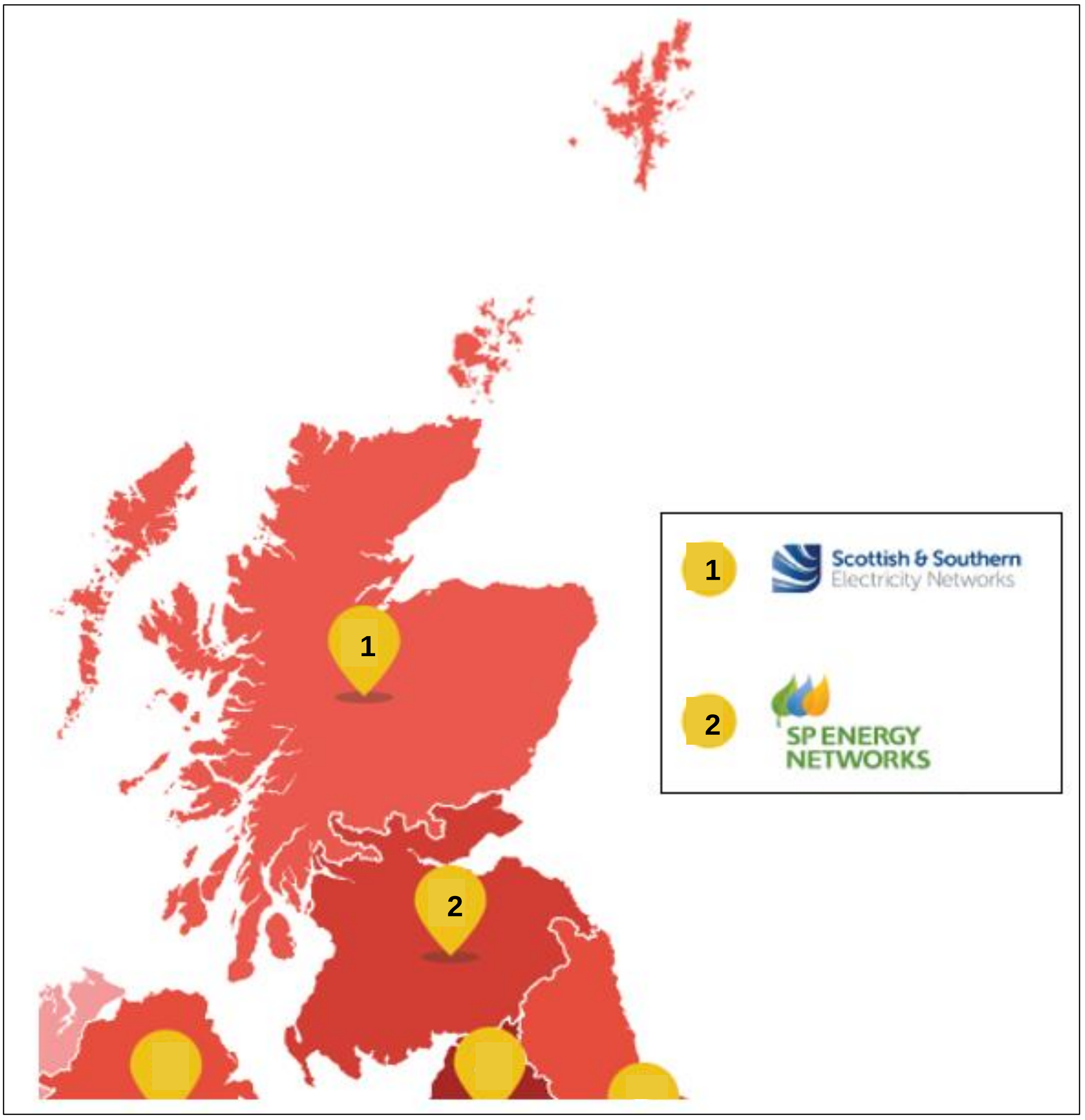
Note that the fuel costs reported for the reforming option will be subject to fluctuations of the cost of natural gas. Additionally, electrolysed hydrogen may be cheaper if produced with low-cost electricity from excess low-carbon power generation, preventing renewables curtailment and providing flexibility to the grid. However, the limited availability of very low-cost electricity is expected to restrict the supply of low-cost hydrogen to 44 TWh in 2050, i.e. ~6% of consumption in the high hydrogen demand scenario[5].

[5] CCC 2018, Hydrogen in a low-carbon economy

2 Network reinforcement costs

A complementary standalone study[6] was conducted by Scottish & Southern Electricity Networks (SSEN) on the impact of future low-carbon electric heating penetration on its area of competency of the Scottish power distribution network competency, see Figure 8.

Figure 8: UK electricity distribution network operators[7]

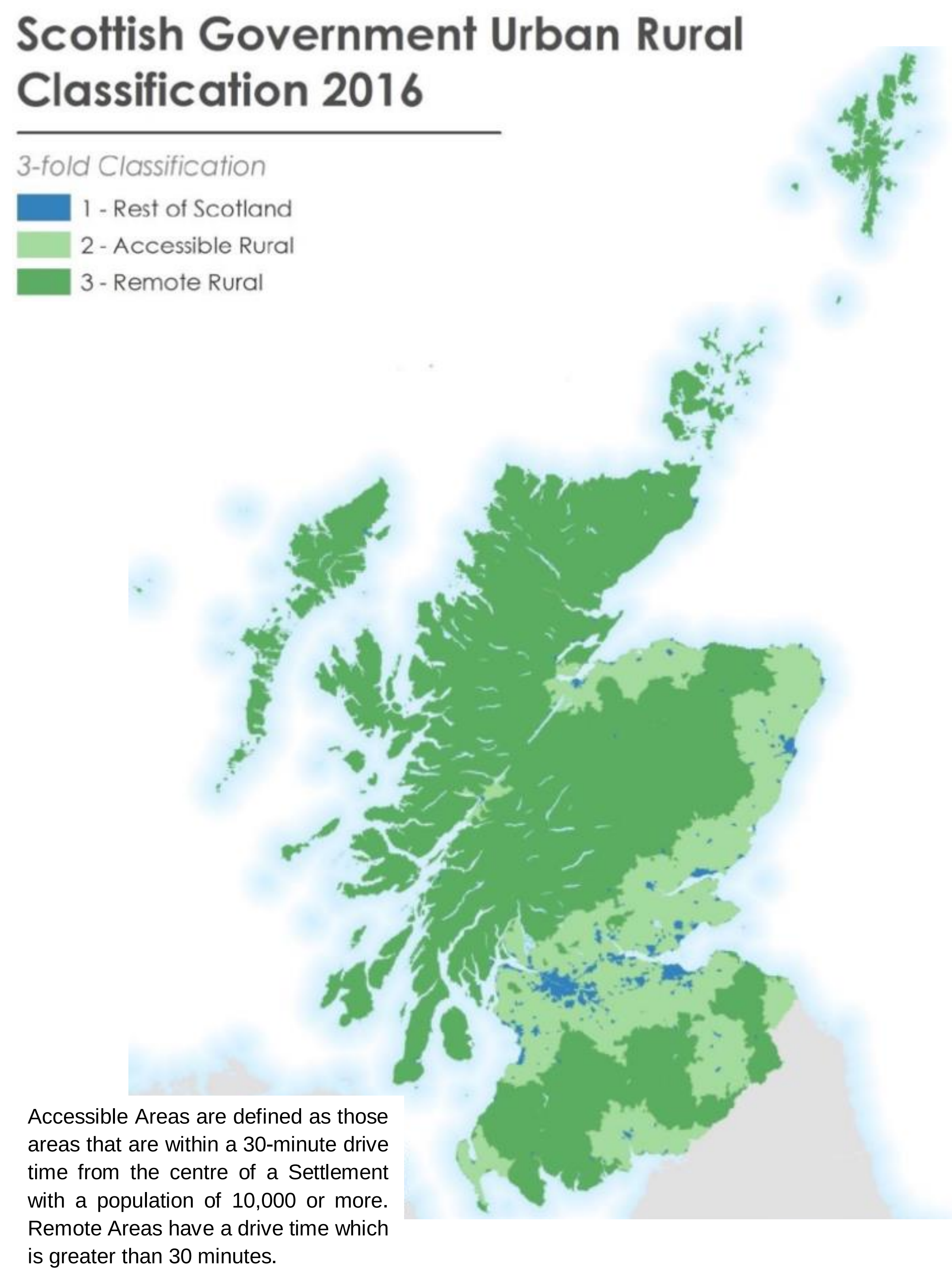


The secondary substation and Low Voltage levels of the Network were modelled by SSEN to examine the technical and economic impact of the future installation of electric heating and heat pumps per plot for each of the classifications in the Scottish Governments Urban and Rural 3-fold model. Figure 9 shows the geographical location across the Scottish territory of

[6] Scottish & Southern Electricity Networks 2019, Impact of Future Electric Heating Penetration on SSEN's network in Scotland using the Scottish Government's Urban and Rural Classifications
[7] ENA, Electricity Distribution Map

the area classifications: Rest of Scotland (blue), Accessible Rural (light green), Remote Rural (dark green).

Figure 9: Scottish Government 3-fold Urban Rural Classification 2016[8]



[8] Scottish Government, Urban Rural Classification 2016

The amount of heating systems already installed was assessed for a range of different heating types in each of the three areas and the load of electric heating units that could potentially be installed in future was estimated. The number and size of secondary transformers, average number of LV feeders and customer per transformer was calculated to produce the cost of network upgrade interventions.

The results of this analysis are given for both uptake of **conventional electric** and **heat pump** heating across the Scottish Government's Urban and Rural classifications and are summarised in Table 13.

Table 13: Cost per plot for each of the Scottish Government's Urban and Rural classification for the 3-fold model for both conventional electric heating and HPs

Area Classification	Heat Pump uptake (£/plot)	Direct electric uptake (£/plot)
1 - Rest of Scotland	£489	£539
2 - Accessible Rural	£1,532	£1,586
3 - Remote Rural	£1,653	£1,698

The analysis found the cost of network reinforcement in urban areas to be substantially lower than for rural areas, also due to the average larger size of the transformers. Additionally, the smaller load carried by the uptake of heat pumps, as opposed to direct electric heating, requires more modest intervention and lower costs.

While the overall cost of network upgrade (for secondary substation and low voltage levels) due to the implementation of low-carbon heating is not particularly large, total cost will need to consider also additional upgrades that will be required to support the electrification of transport. While these additional measures will contribute to increase the total cost of the upgrades, this will be shared across different energy services.

3 Cost of low-carbon heating for common dwelling archetypes

The cost of the considered low-carbon heating technologies was investigated for 10 of the most common dwelling archetypes.

The selected archetypes include the 8 most populated archetypes, ranking highest in terms of the portion of the stock they represent. Additionally, the 13th and 22nd archetypes were also considered, as these are the most populated archetypes for which the counterfactual heating technology is oil boiler and electric heating respectively.

The characteristics of the 10 selected archetypes are summarised in Table 14. These archetypes are relatively diversified in terms of dwelling type, size, age and insulation characteristics, but their counterfactual heating technology is gas boiler for the majority of them. All archetypes represent together ~500 thousand homes, capturing ~20% of Scotland's housing stock.

Table 14: Characteristics of the selected most common archetypes

Archetype ranking	Property Type	Size	Age	Wall Insulation	Roof Insulation (mm)	Counterfactual	Space heating demand in 2020 (kWh/yr)	Space heating demand in 2040 (kWh/yr)	Hot water demand in 2020 and 2040 (kWh/yr)	Stock
1	Semi detached	Medium	1919 to 1991	CWI	More than 250	Gas boiler	10,144	8,383	2,251	**111,180**
2	Flat (other)	Small	Pre 1919	SWU	None	Gas boiler	6,345	3,272	1,426	**64,389**
3	Flat (other)	Medium	1919 to 1991	CWI	None	Gas boiler	7,134	5,522	1,901	**55,533**
4	Semi detached	Medium	1919 to 1991	CWI	100 to 250	Gas boiler	10,358	8,779	2,298	**55,427**
5	Flat (other)	Small	1919 to 1991	CWI	None	Gas boiler	5,640	4,272	1,646	**47,361**
6	Flat (other)	Medium	Pre 1919	SWU	None	Gas boiler	9,608	5,747	1,854	**45,069**
7	Detached	Large	Post 1991	SWI	More than 250	Gas boiler	11,571	10,756	1,671	**40,928**
8	Terraced	Medium	1919 to 1991	CWI	More than 250	Gas boiler	9,089	7,028	2,150	**37,325**
13	Detached	Large	Pre 1919	SWU	Room in roof	Oil boiler	26,130	16,148	2,956	**20,288**
22	Flat (other)	Small	Pre 1919	SWU	None	Electric storage	6,321	4,312	1,420	**17,245**

The following sections report the results of this study on the cost of each investigated low-carbon heating technology for the above reported common archetypes. For each technology, the total cost is shown disaggregated into the four main cost components: heating system cost, maintenance cost, additional cost and fuel cost. The technologies labelled in red are those for which the considered archetype is unsuitable, considering fuse limit of 80A and peak specific heating demand of 120 W/m^2.

For these outputs the cost of hydrogen from both electrolysis and reforming was assumed to be that of the high demand scenario. The fuel utilised by hybrid heat pumps was assumed to be hydrogen from reforming. [9]

[9] It is worth noting that these "building archetypes" are not inherently on or off the gas grid. Each "building archetype" is in fact associated with a subset of "detailed archetypes" that describe further characteristics of a property, including its location on or off the gas grid. As a result, a particular "building archetype" is always described by a share of "detailed archetypes" that are either on or off the gas grid.

3.1 Archetype 1

Figure 10: Cost of the investigated technologies for archetype 1 in 2020

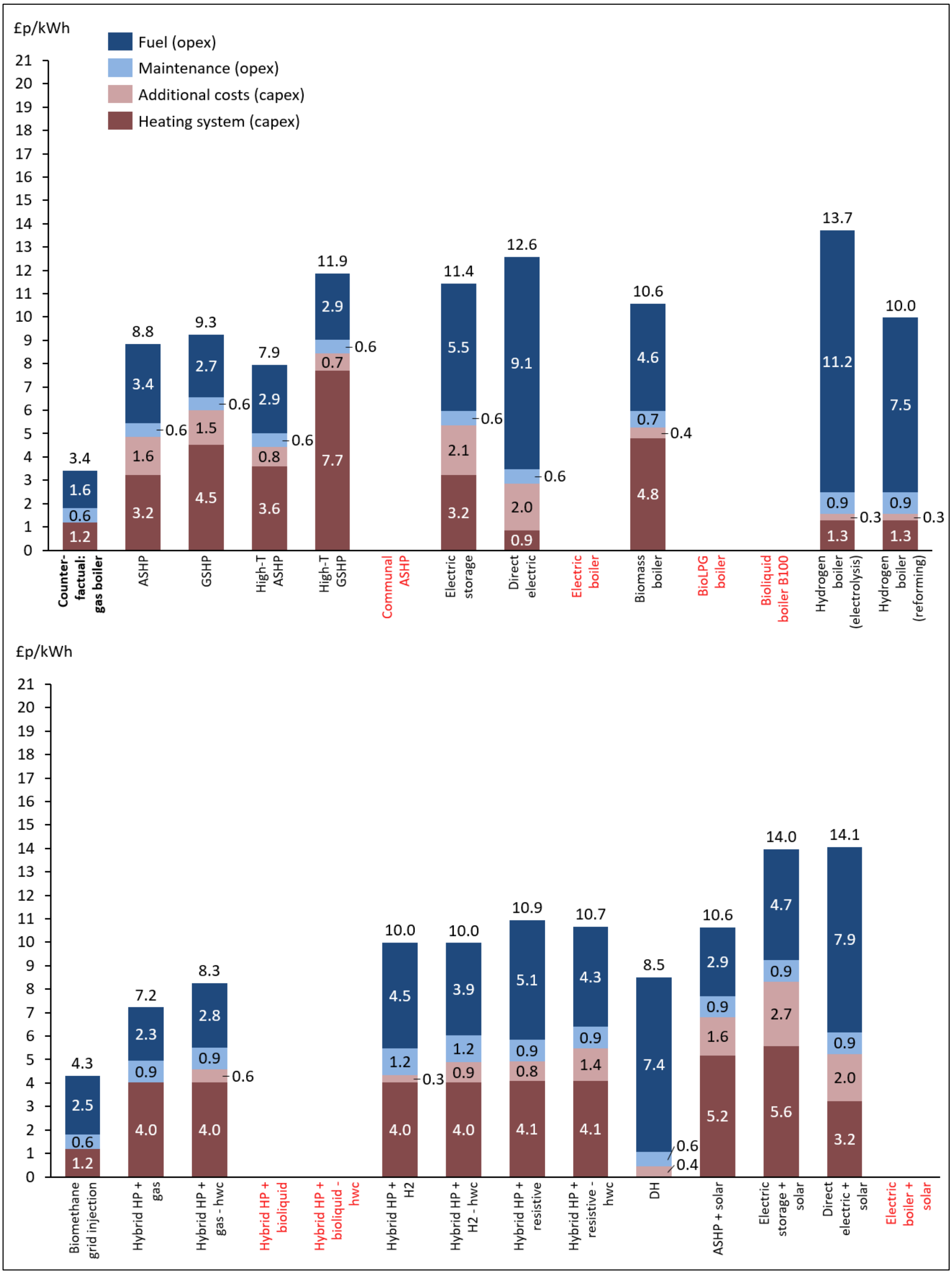
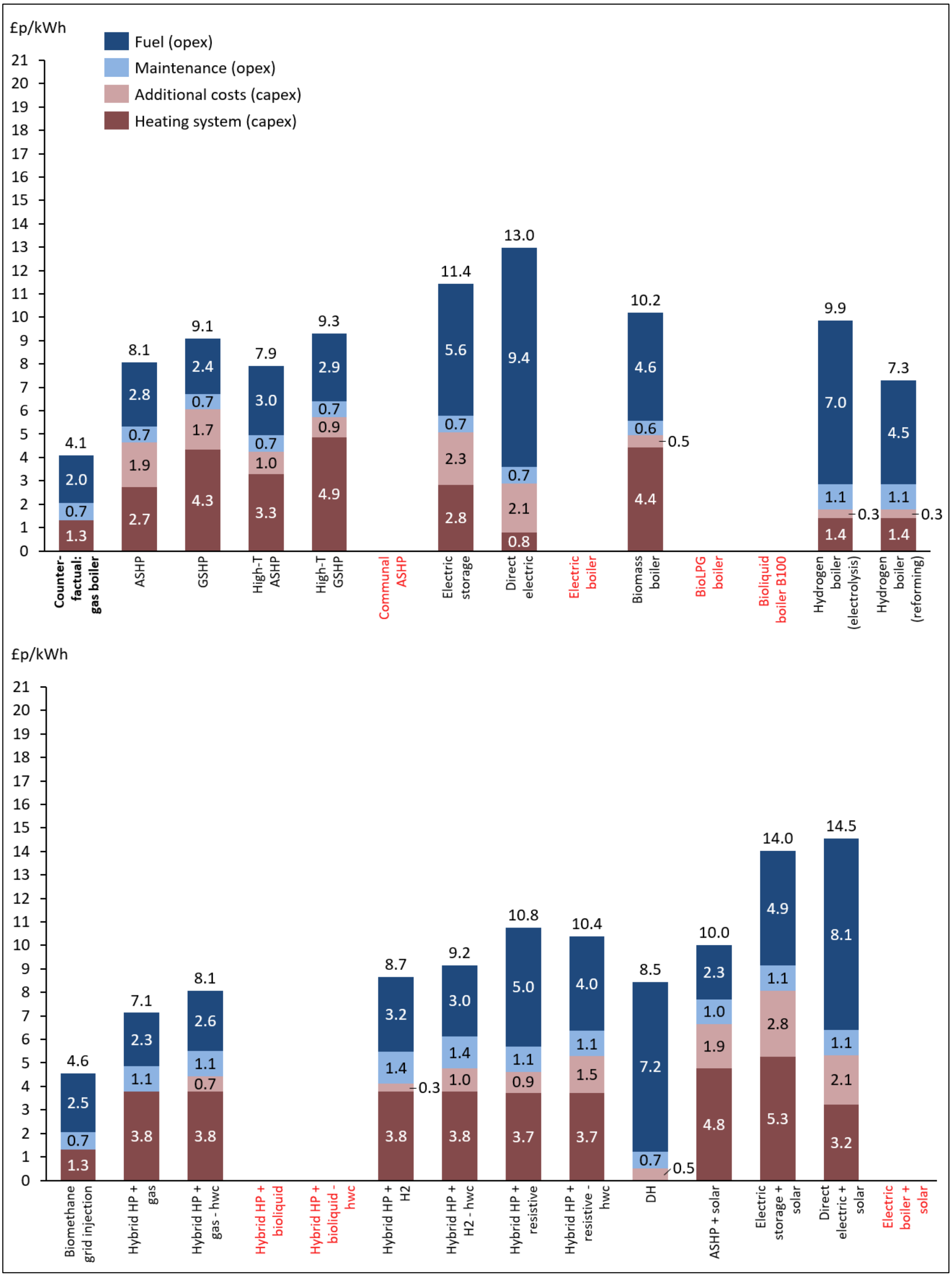


Figure 11: Cost of the investigated technologies for archetype 1 in 2040



3.2 Archetype 2

Figure 12: Cost of the investigated technologies for archetype 2 in 2020

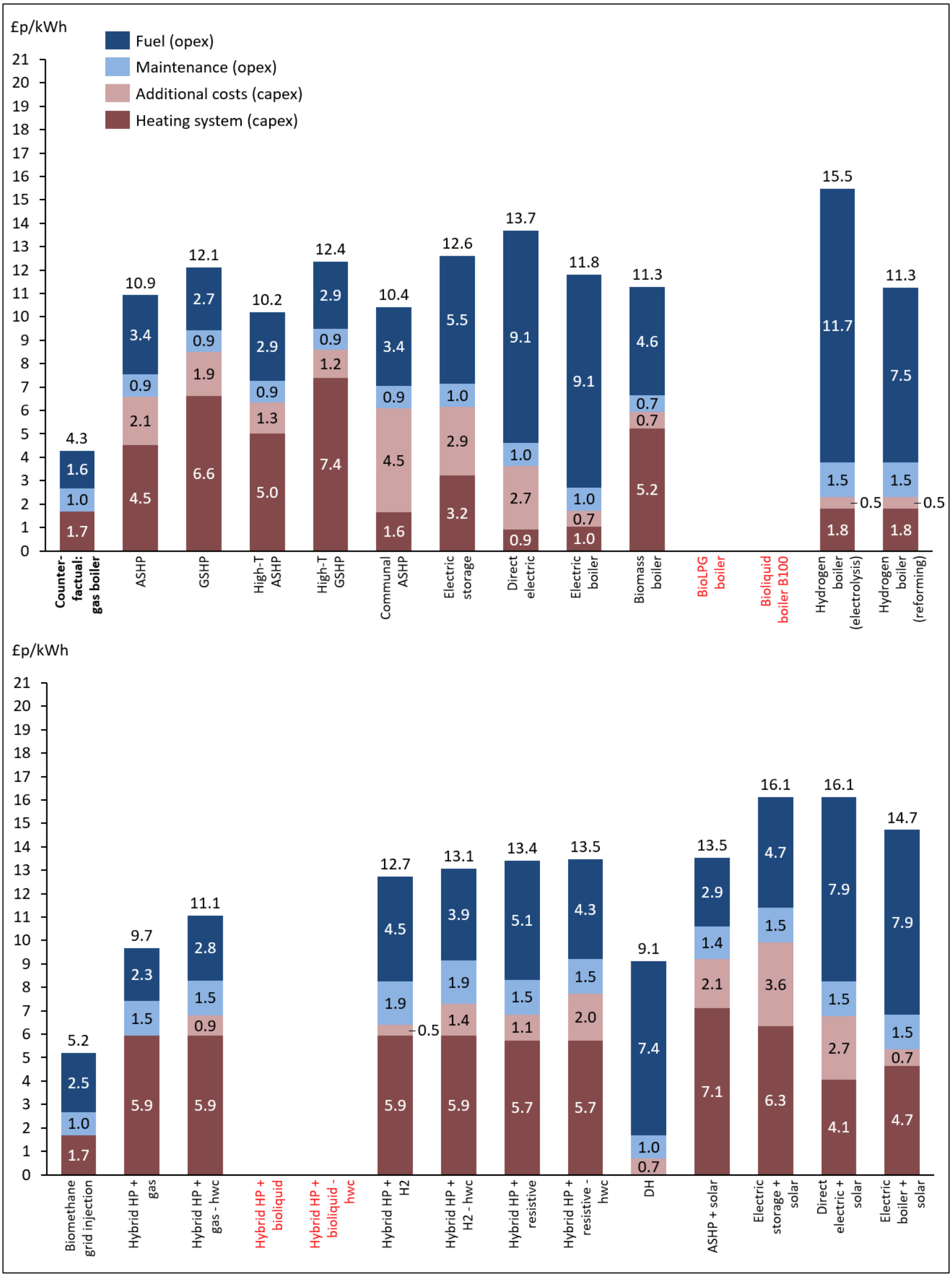
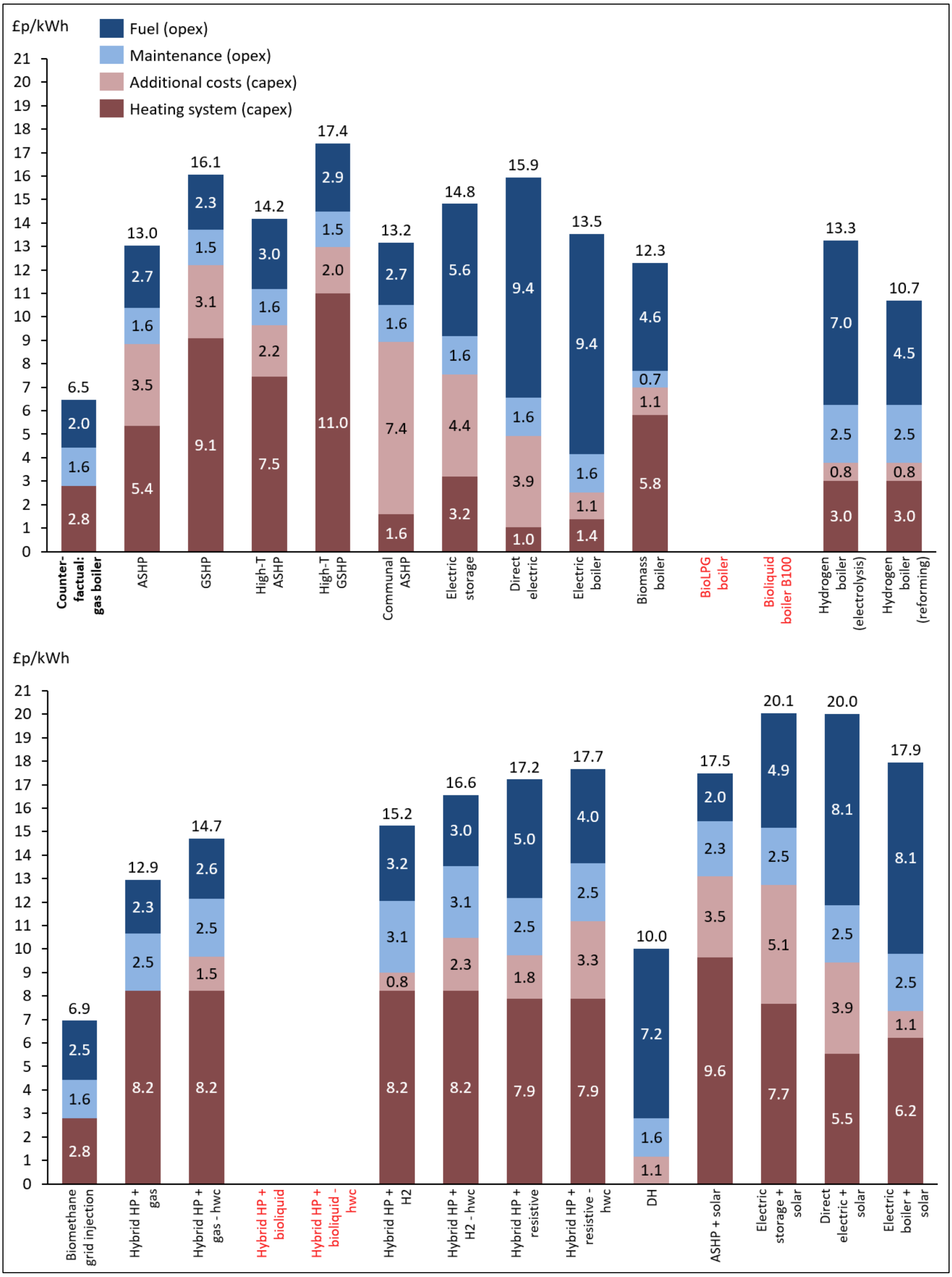


Figure 13: Cost of the investigated technologies for archetype 2 in 2040



3.3 Archetype 3

Figure 14: Cost of the investigated technologies for archetype 3 in 2020

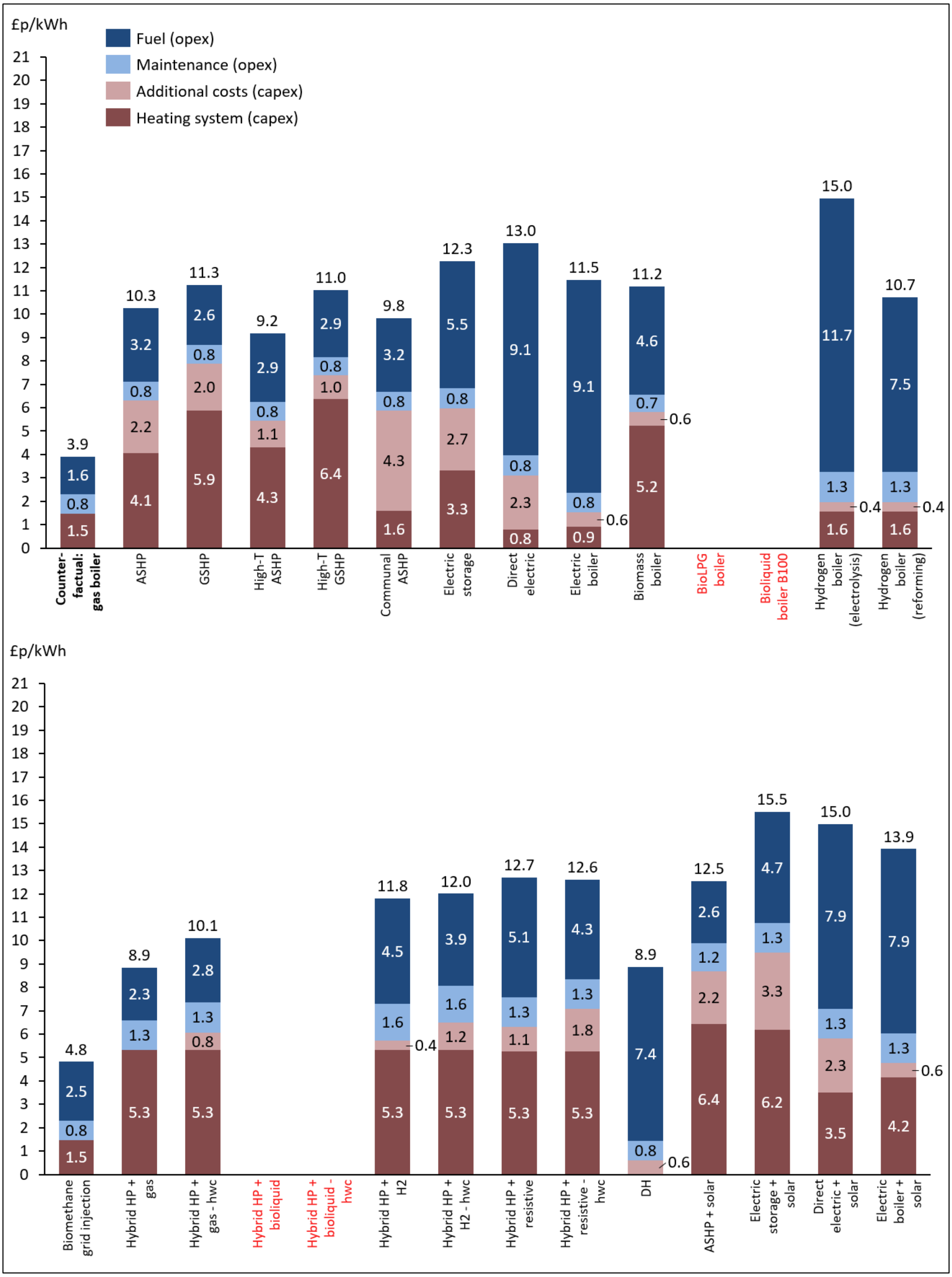
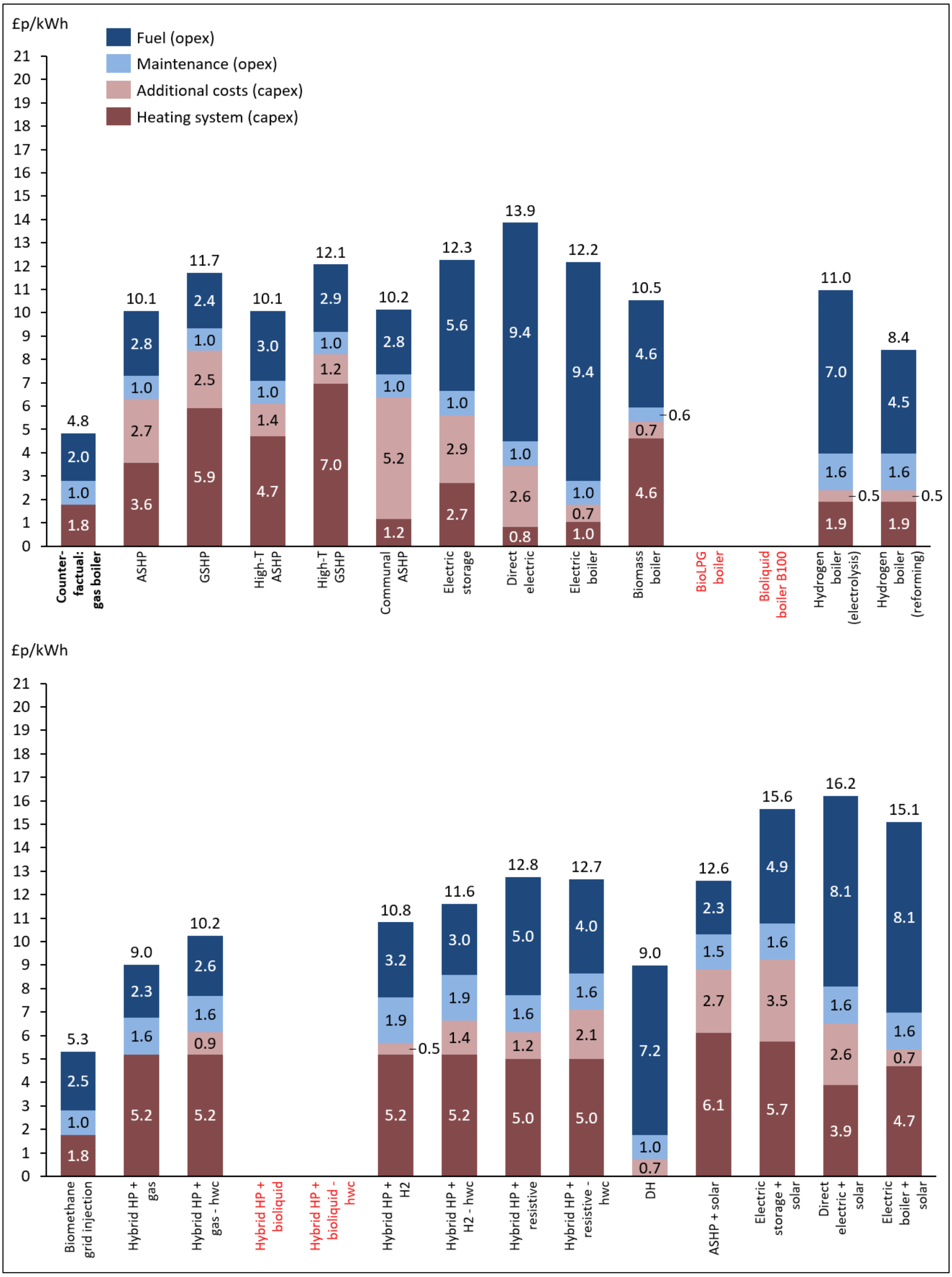


Figure 15: Cost of the investigated technologies for archetype 3 in 2040



3.4 Archetype 4

Figure 16: Cost of the investigated technologies for archetype 4 in 2020

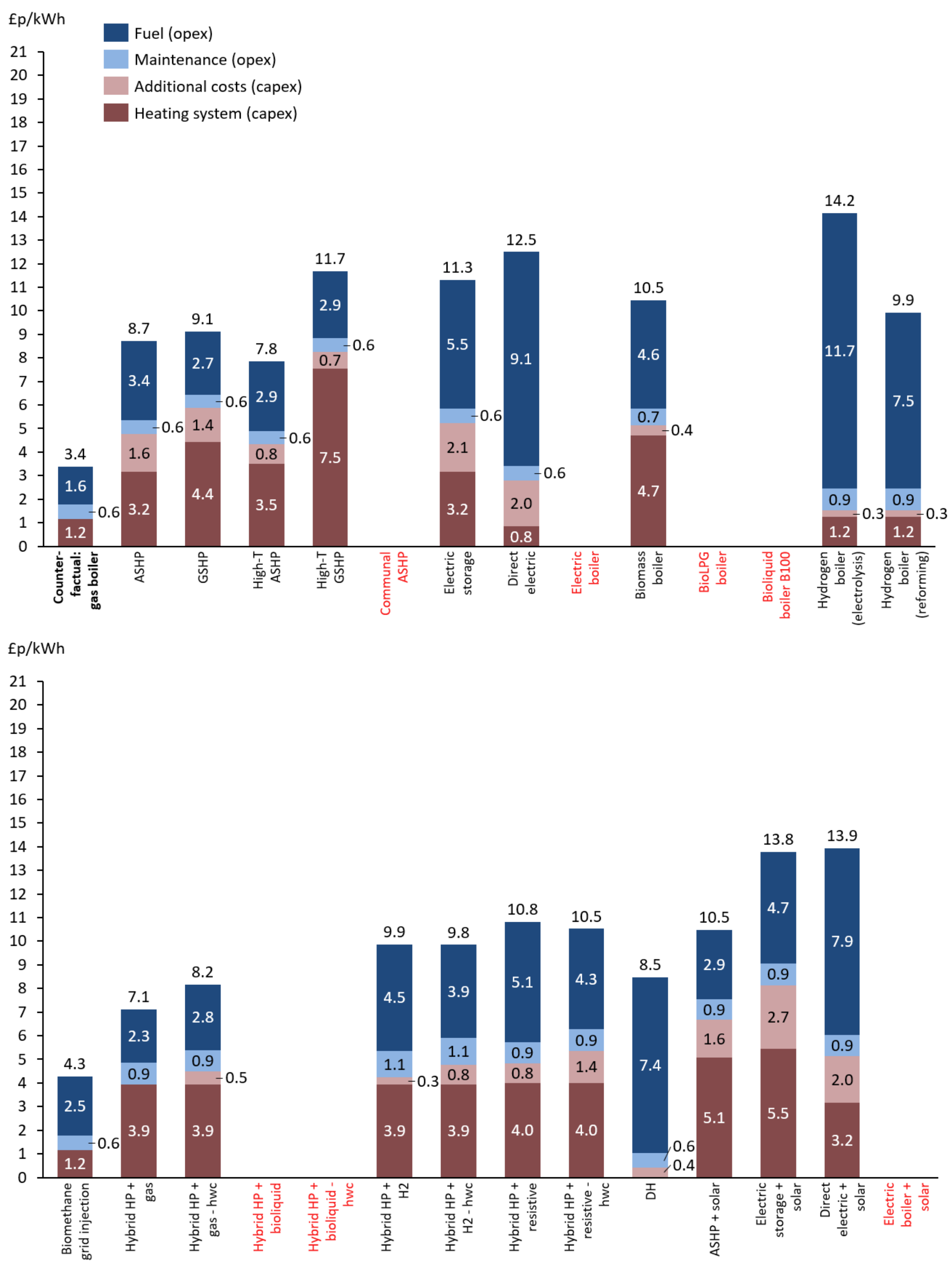
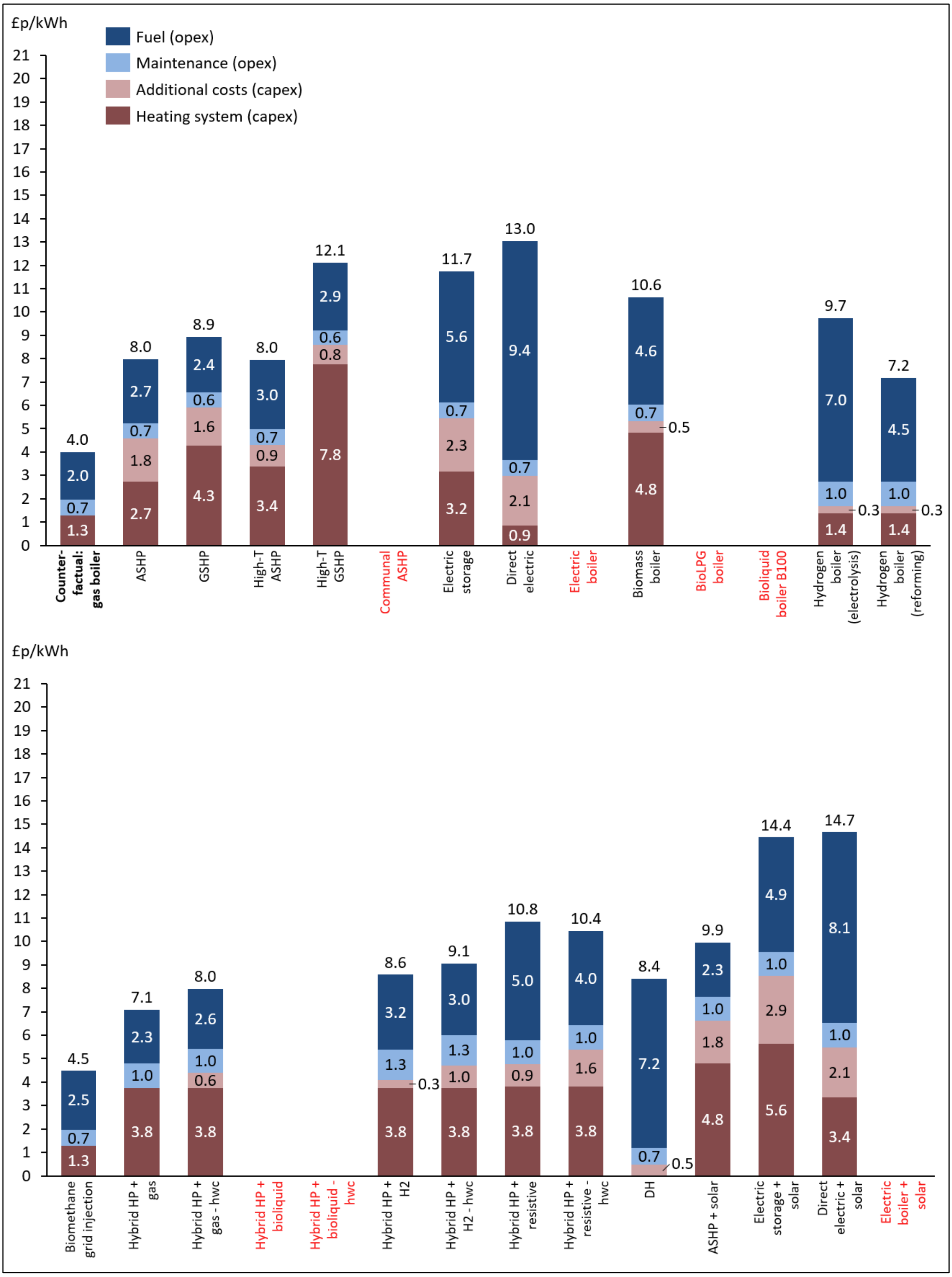


Figure 17: Cost of the investigated technologies for archetype 4 in 2040



3.5 Archetype 5

Figure 18: Cost of the investigated technologies for archetype 5 in 2020

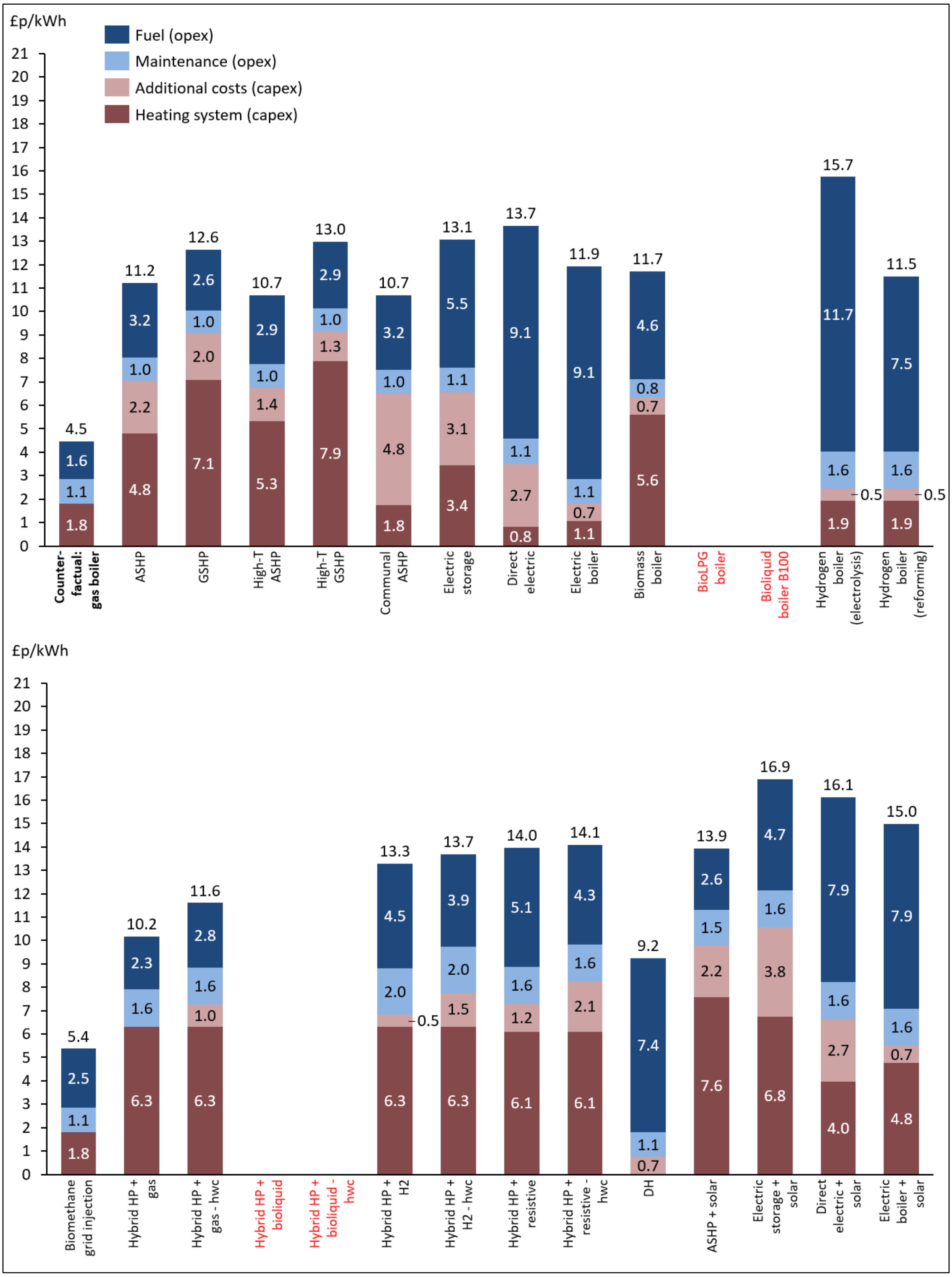
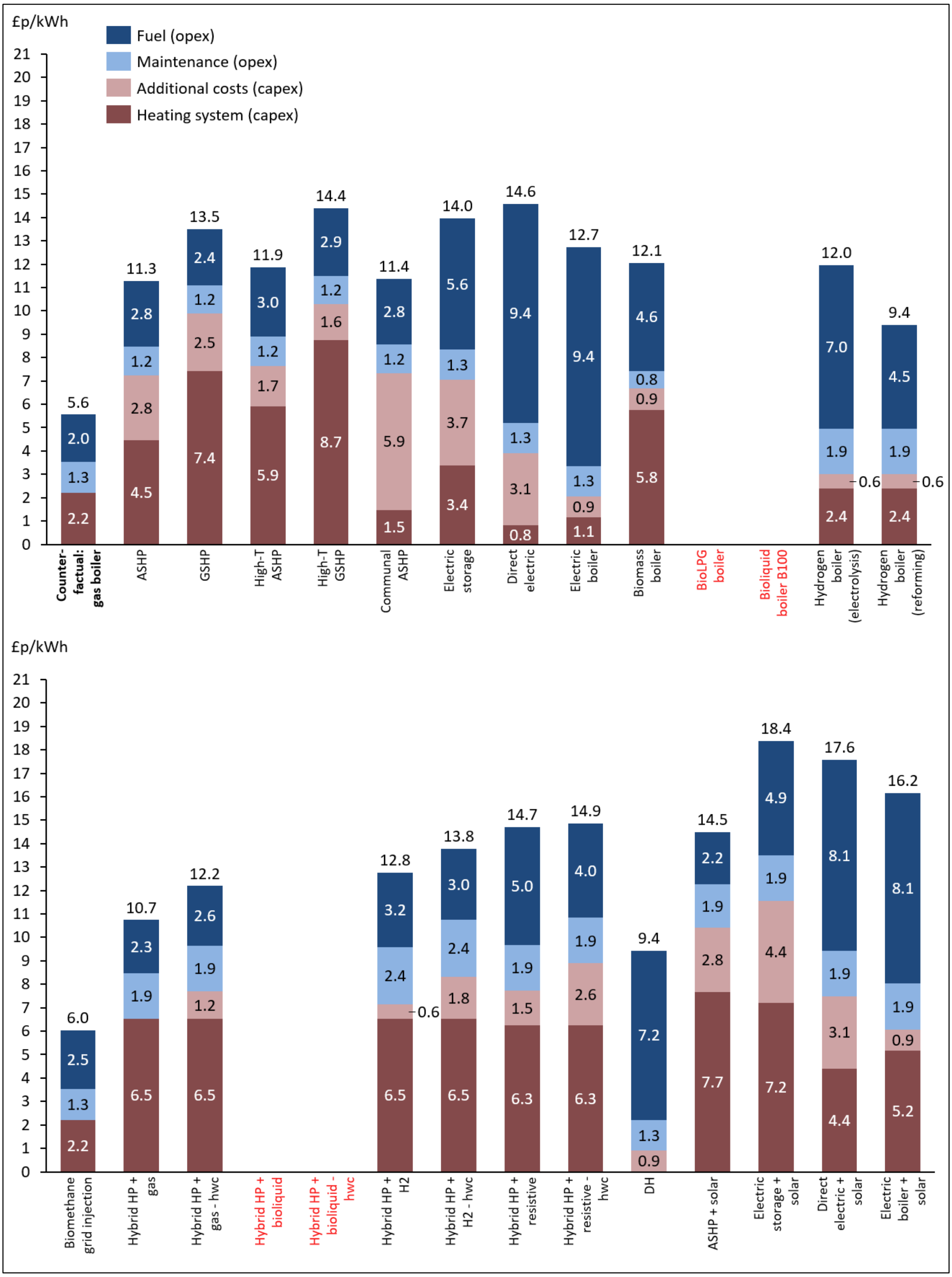


Figure 19: Cost of the investigated technologies for archetype 5 in 2040



Technology	Heating system (capex)	Additional costs (capex)	Maintenance (opex)	Fuel (opex)	Total
Counter-factual: gas boiler	2.2		1.3	2.0	5.6
ASHP	4.5	2.8	1.2	2.8	11.3
GSHP	7.4	2.5	1.2	2.4	13.5
High-T ASHP	5.9	1.7	1.2	3.0	11.9
High-T GSHP	8.7	1.6	1.2	2.9	14.4
Communal ASHP	1.5	5.9	1.2	2.8	11.4
Electric storage	3.4	3.7	1.3	5.6	14.0
Direct electric	0.8	3.1	1.3	9.4	14.6
Electric boiler	1.1	0.9	1.3	9.4	12.7
Biomass boiler	5.8	0.9	0.8	4.6	12.1
BioLPG boiler					
Bioliquid boiler B100					
Hydrogen boiler (electrolysis)	2.4	0.6	1.9	7.0	12.0
Hydrogen boiler (reforming)	2.4	0.6	1.9	4.5	9.4
Biomethane grid injection	2.2		1.3	2.5	6.0
Hybrid HP + gas	6.5		1.9	2.3	10.7
Hybrid HP + gas - hwc	6.5	1.2	1.9	2.6	12.2
Hybrid HP + bioliquid					
Hybrid HP + bioliquid - hwc					
Hybrid HP + H2	6.5	0.6	2.4	3.2	12.8
Hybrid HP + H2 - hwc	6.5	1.8	2.4	3.0	13.8
Hybrid HP + resistive	6.3	1.5	1.9	5.0	14.7
Hybrid HP + resistive - hwc	6.3	2.6	1.9	4.0	14.9
DH		0.9	1.3	7.2	9.4
ASHP + solar	7.7	2.8	1.9	2.2	14.5
Electric storage + solar	7.2	4.4	1.9	4.9	18.4
Direct electric + solar	4.4	3.1	1.9	8.1	17.6
Electric boiler + solar	5.2	0.9	1.9	8.1	16.2

3.6 Archetype 6

Figure 20: Cost of the investigated technologies for archetype 6 in 2020

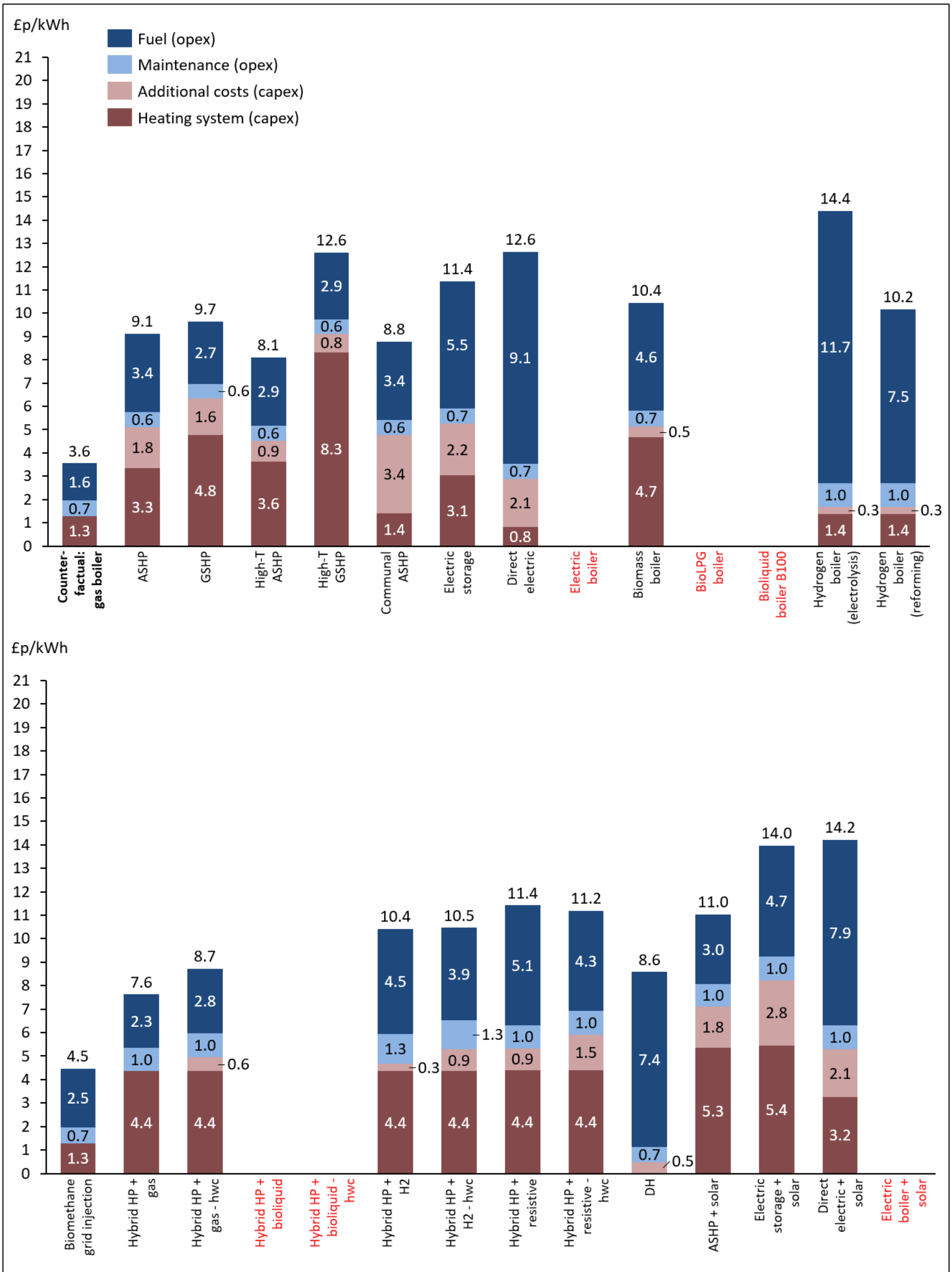
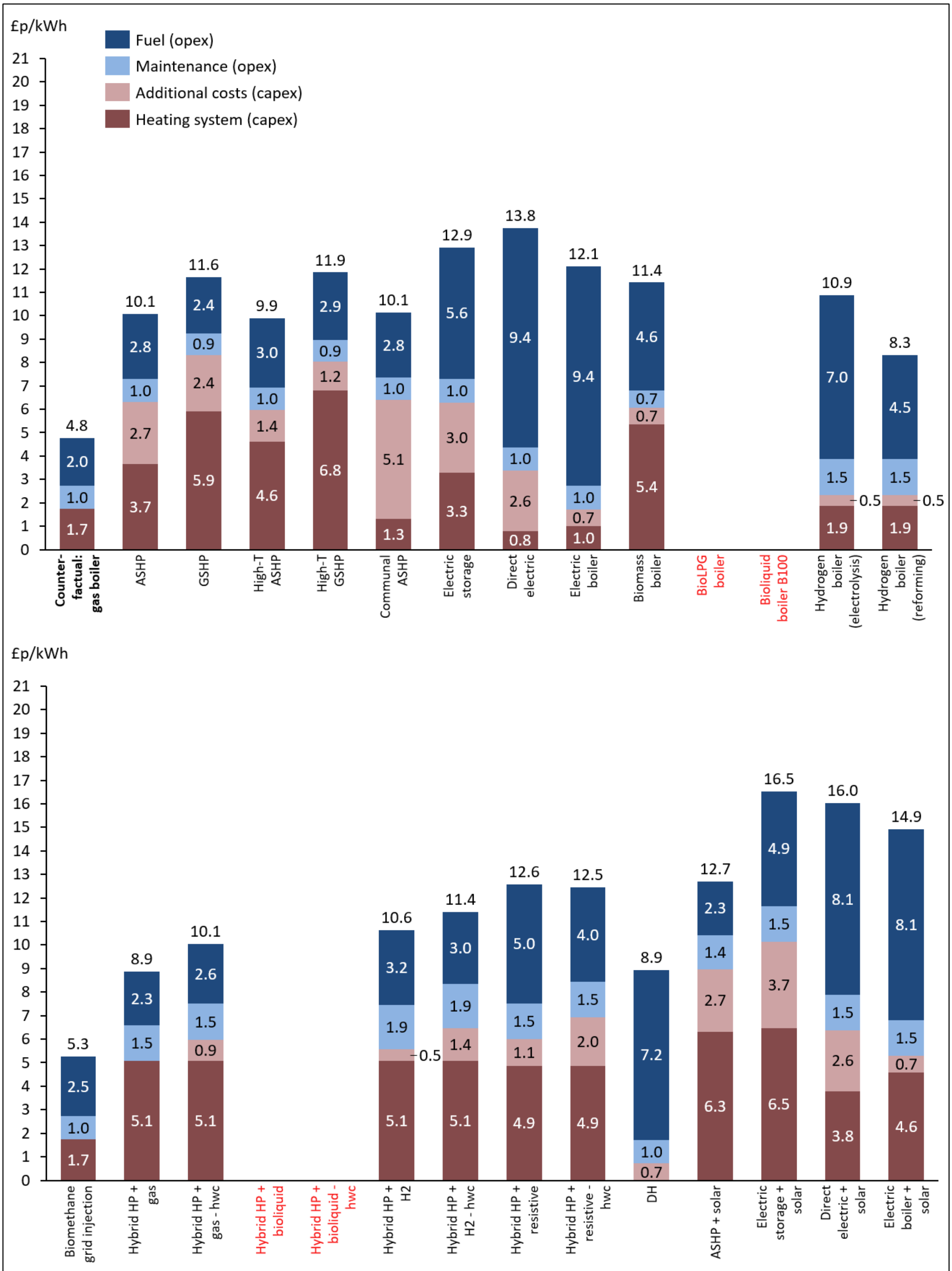


Figure 21: Cost of the investigated technologies for archetype 6 in 2040



3.7 Archetype 7

Figure 22: Cost of the investigated technologies for archetype 7 in 2020

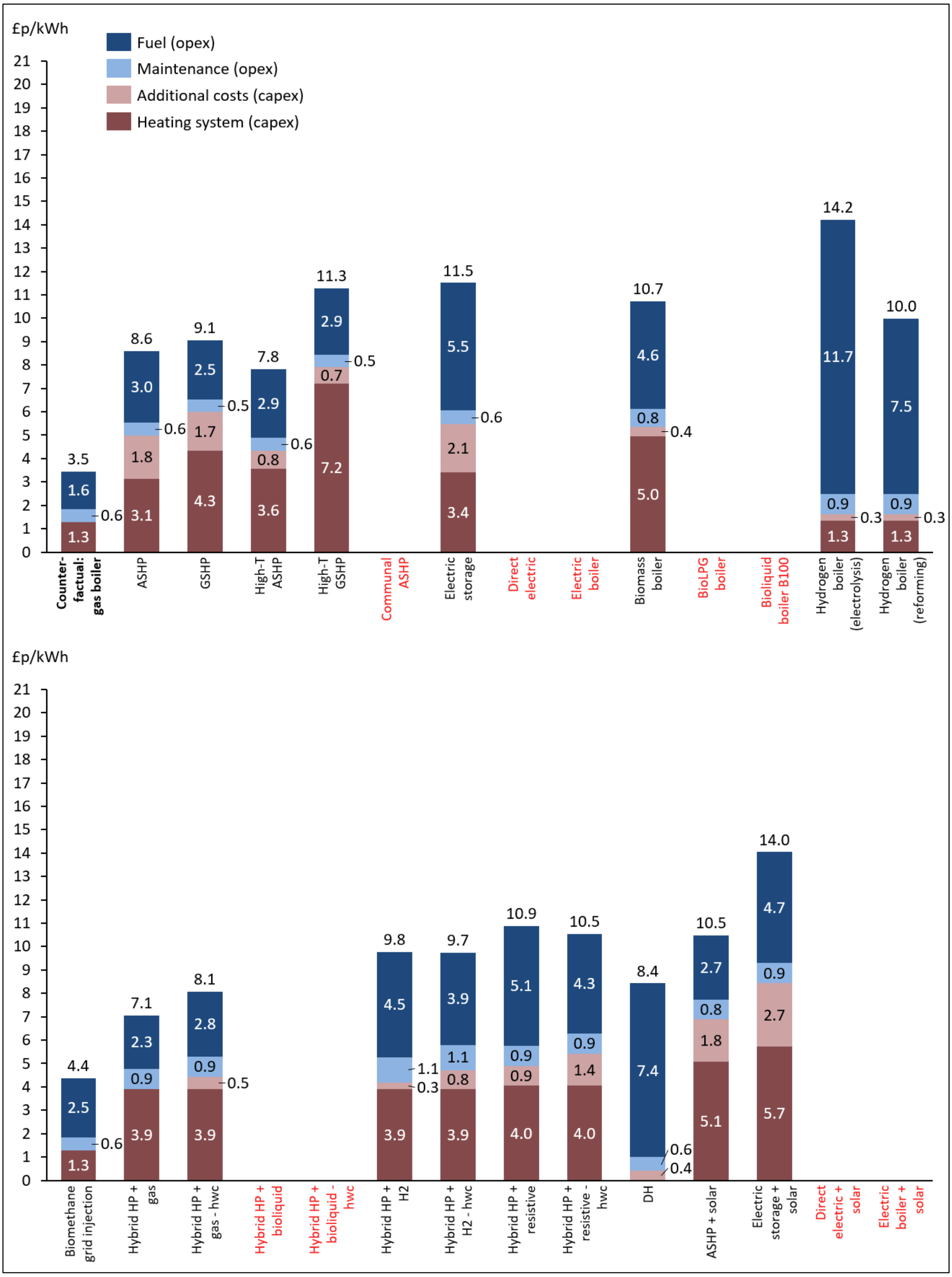
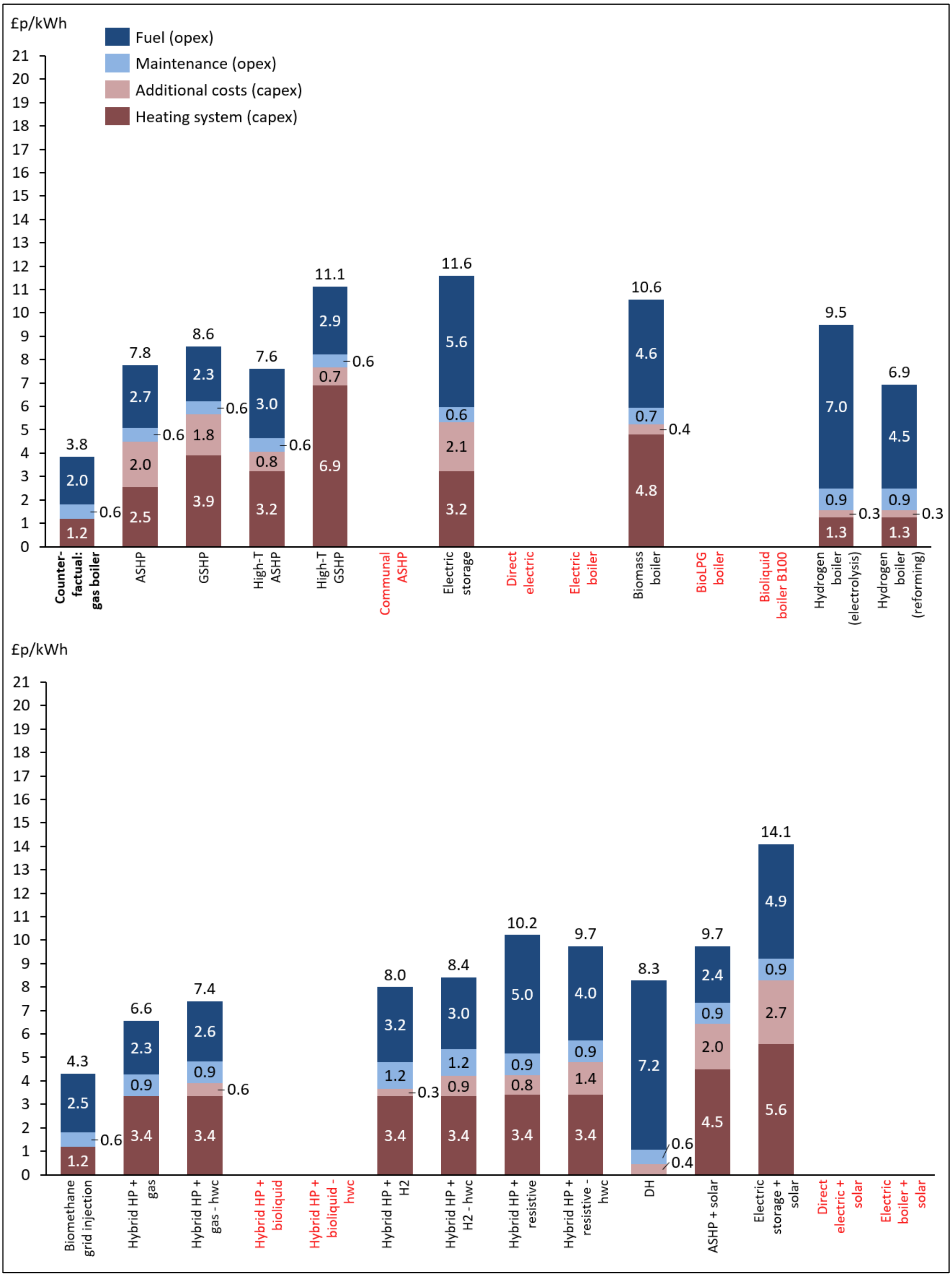


Figure 23: Cost of the investigated technologies for archetype 7 in 2040



3.8 Archetype 8

Figure 24: Cost of the investigated technologies for archetype 8 in 2020

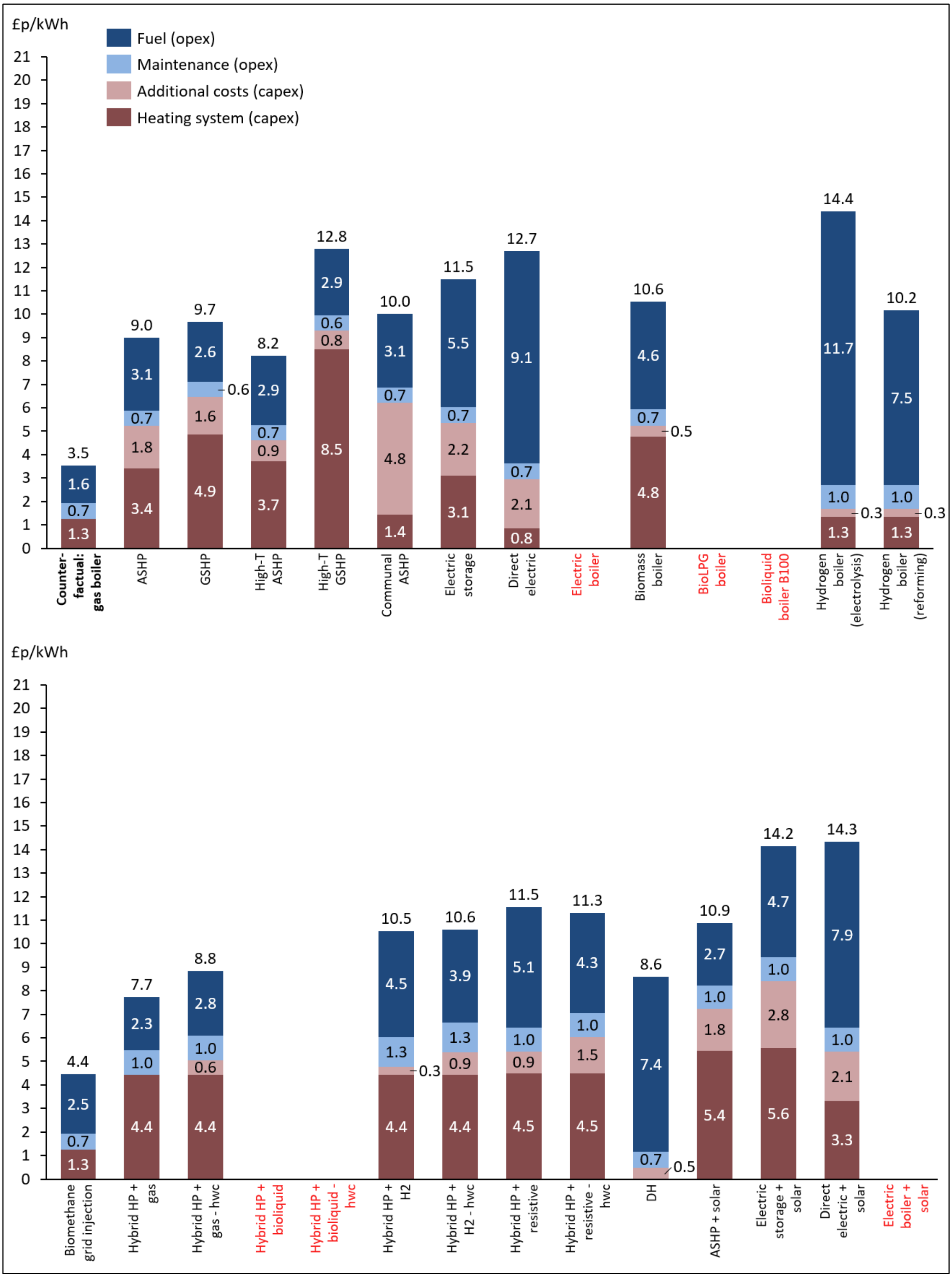
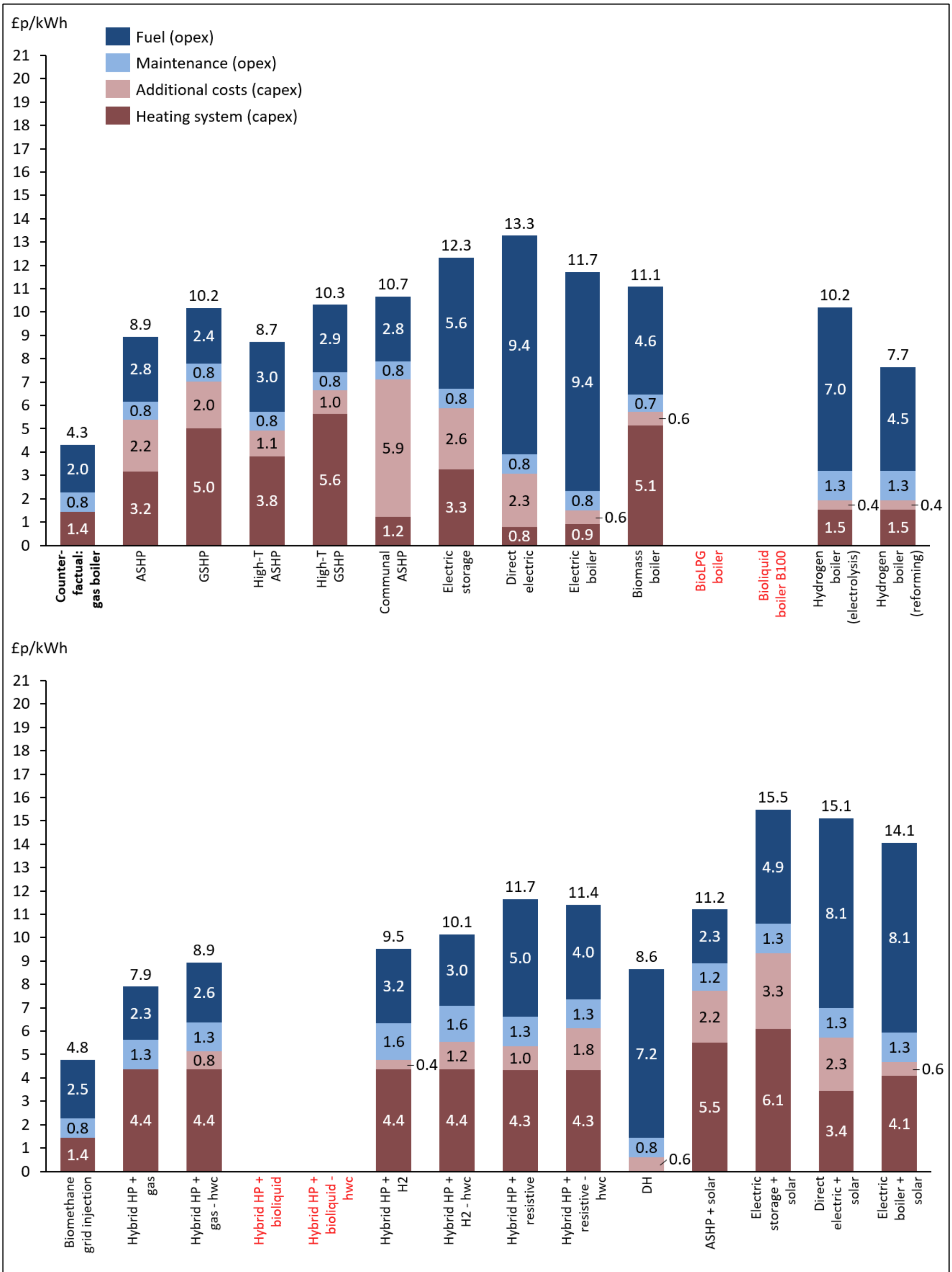


Figure 25: Cost of the investigated technologies for archetype 8 in 2040



3.9 Archetype 13

Figure 26: Cost of the investigated technologies for archetype 13 in 2020

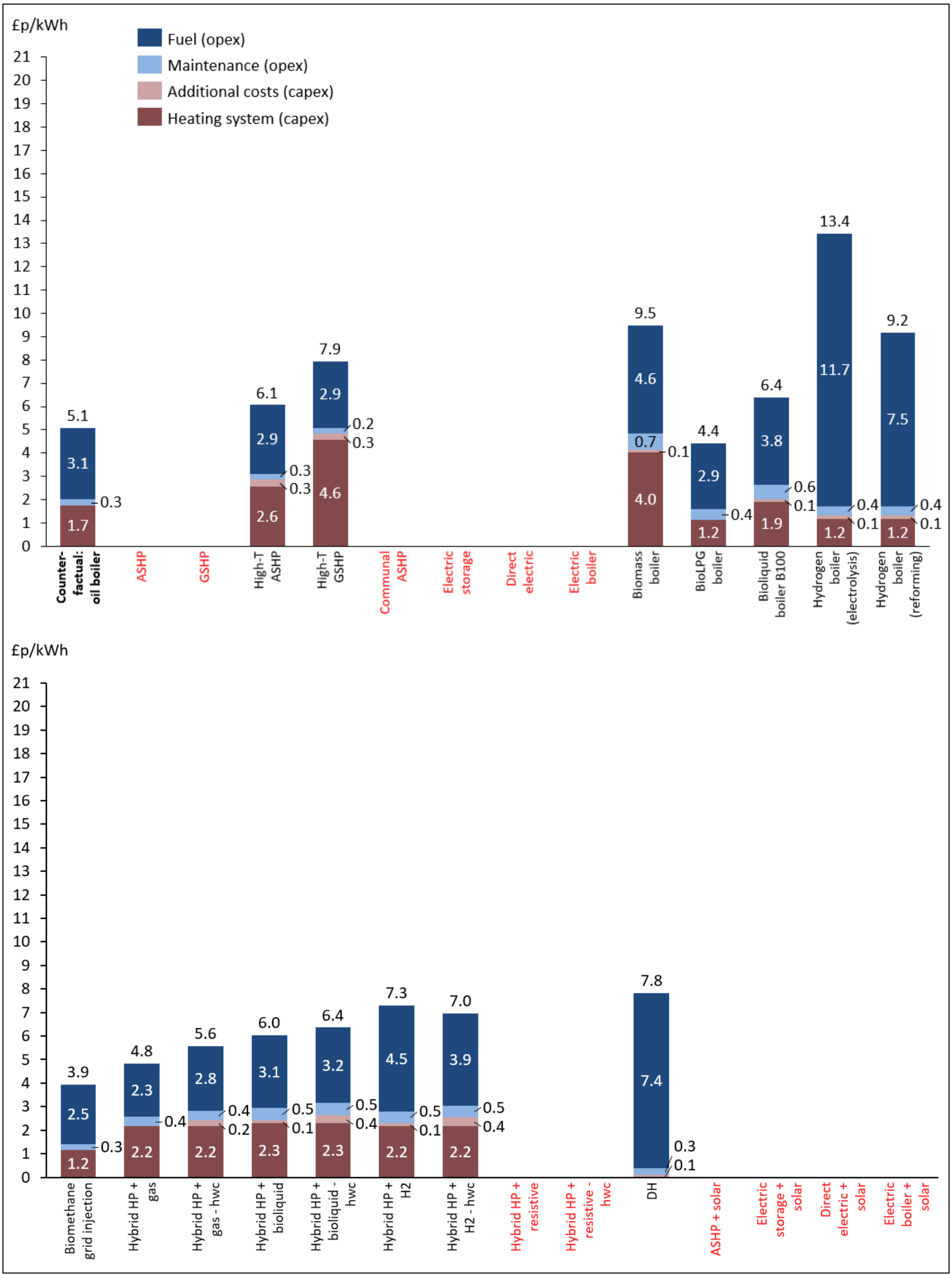
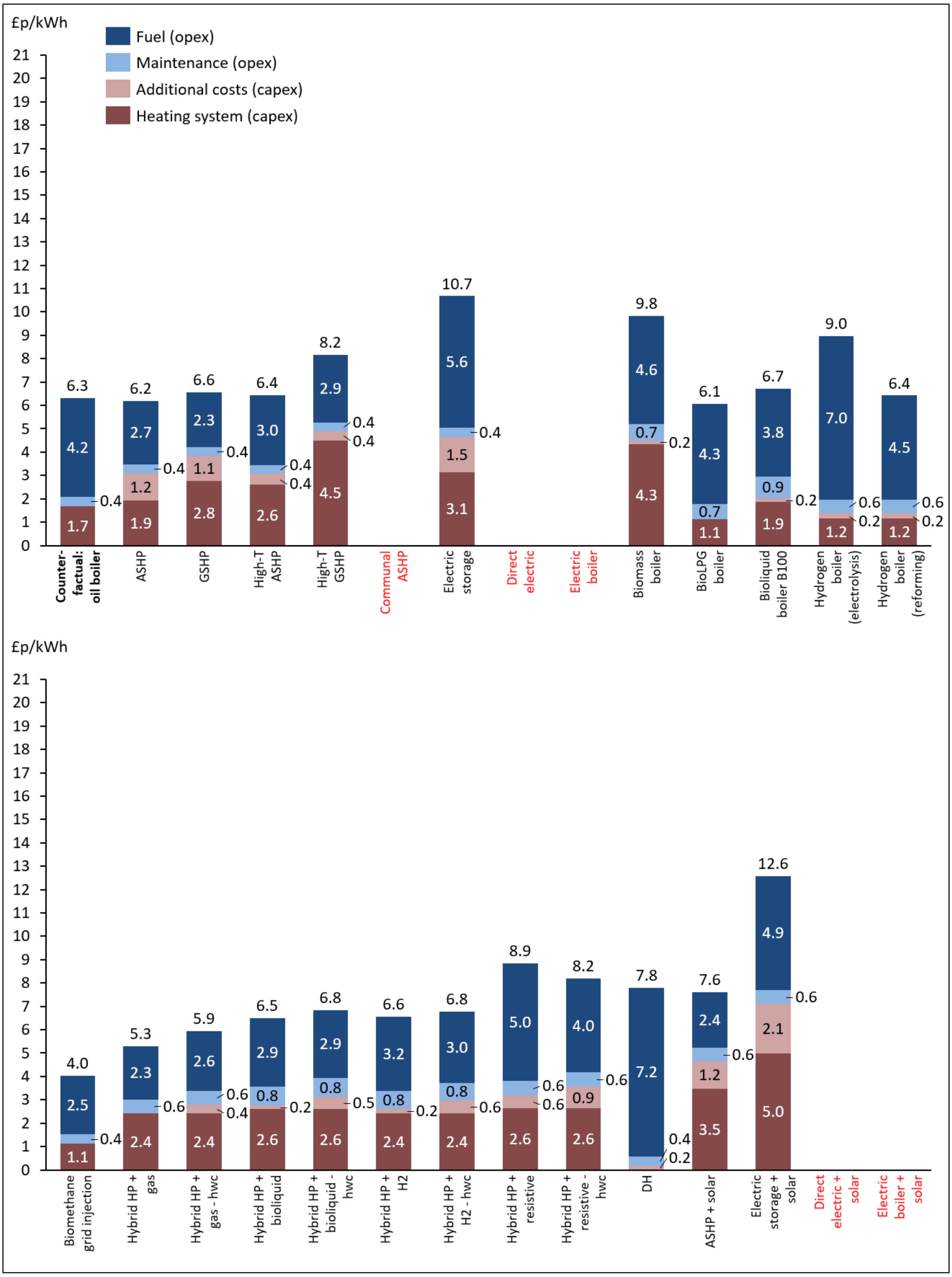


Figure 27: Cost of the investigated technologies for archetype 13 in 2040



3.10 Archetype 22

Figure 28: Cost of the investigated technologies for archetype 22 in 2020

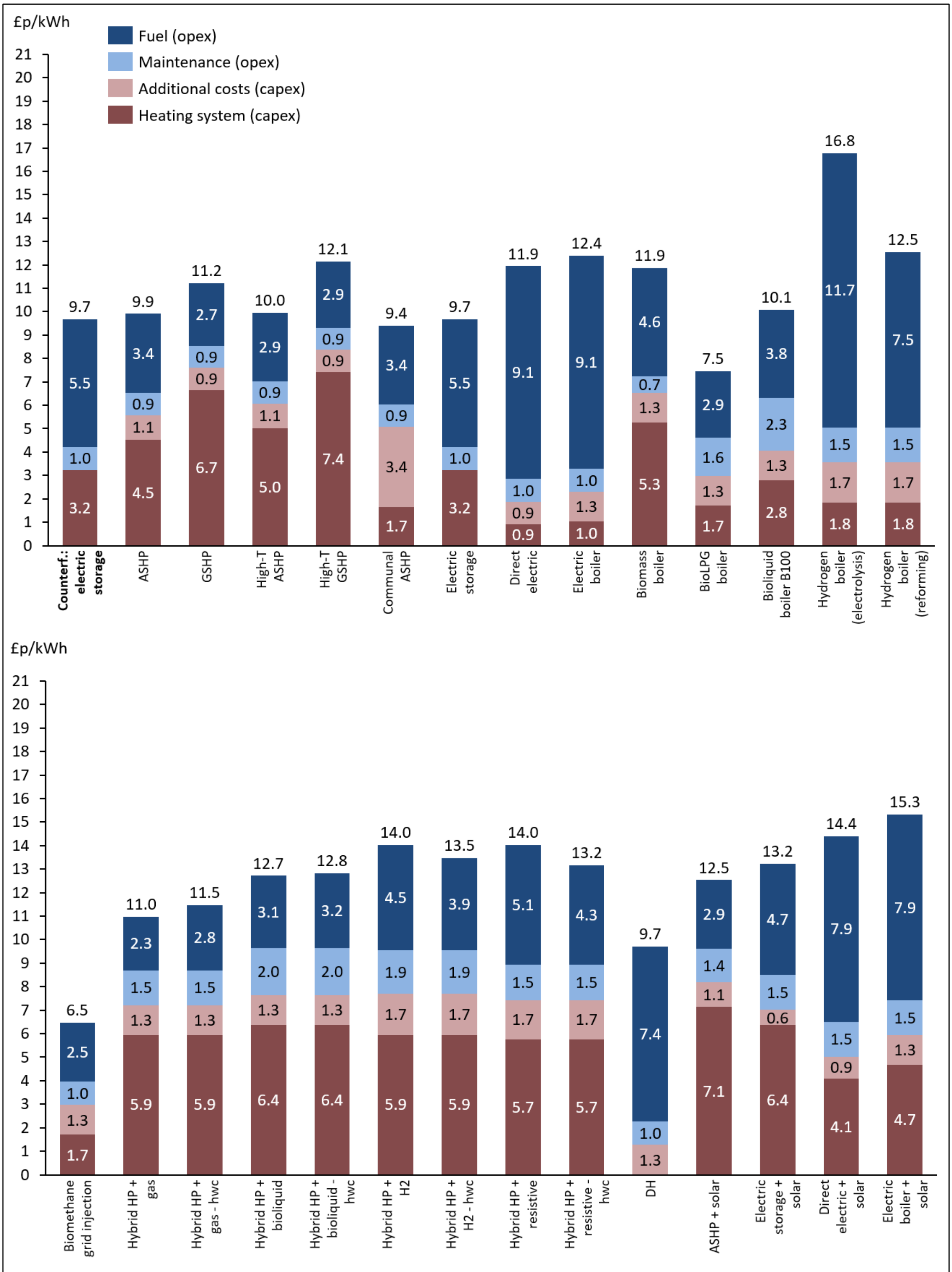
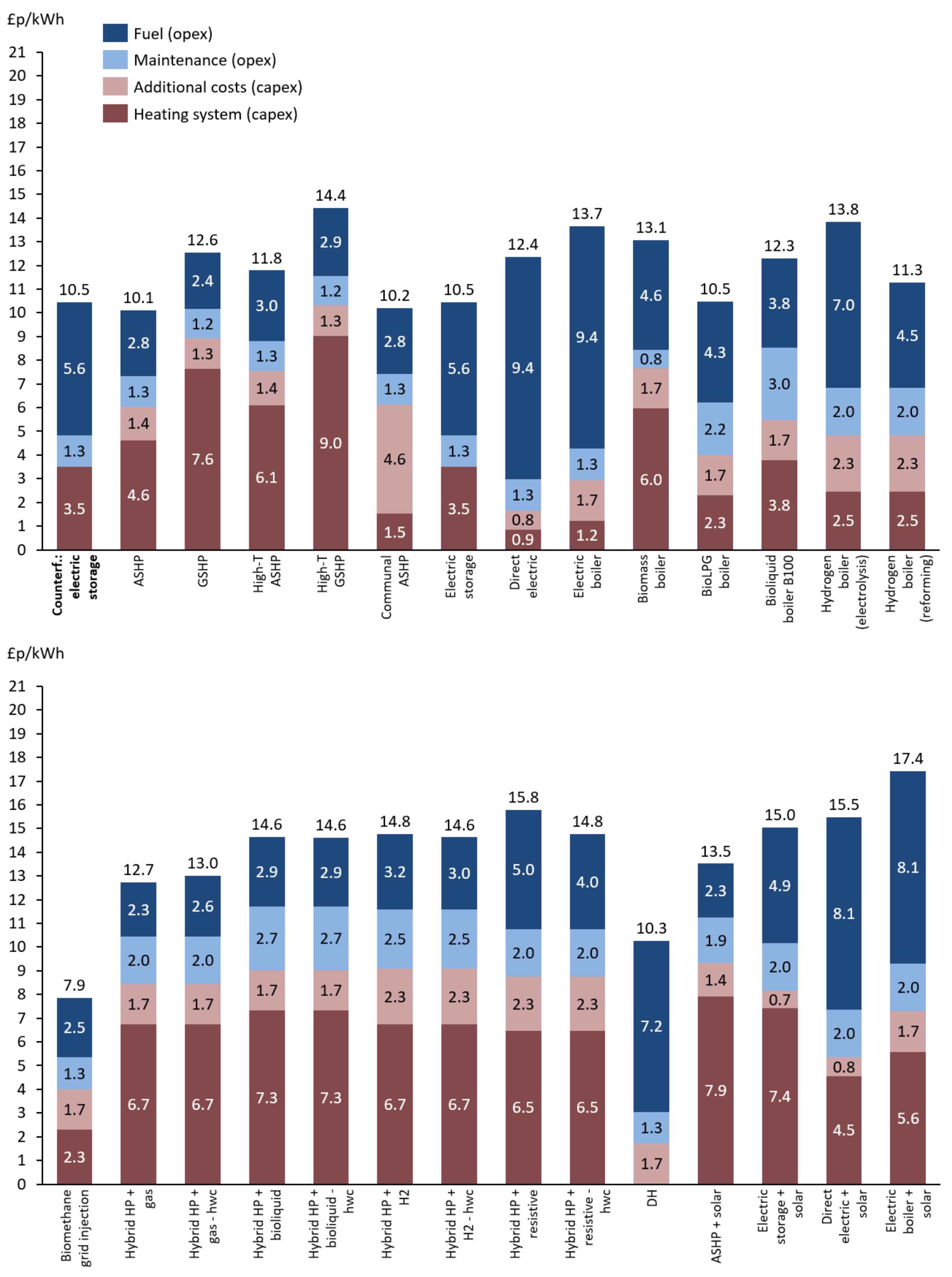


Figure 29: Cost of the investigated technologies for archetype 22 in 2040



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