

# ANNEX

## THE ROLE OF RENEWABLE LIQUID GASES IN EUROPE'S ENERGY TRANSITION – PATHWAYS, BENEFITS, AND POLICY PRIORITIES FOR SCALING UP

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# 1 Demand for rLG in Europe

In this chapter the key assumptions and sensitivities underpinning the indicative demand outlook in Chapter “Demand and Supply for rLG in Europe” are outlined. It provides the detailed household segmentation, switching assumptions, and blending trajectories used to translate residual LPG demand into indicative rLG demand, and also summarises the corresponding assumptions applied for other end-use sectors. The main report presents the headline results and implications; this annex provides the underlying methodological detail.

## 1.1 Household demand

The majority of household heating demand in the EU is currently met by fossil fuels, with gas supplying the largest share of the population. As member states tighten building and heating rules to align with the EU’s climate targets, homes will increasingly need to be heated using renewable or low-carbon energy, implying a large-scale replacement of existing boilers over the coming decades. There is broad political support for electrification through heat pumps, ideally combined with energy-efficient building renovation, as well as for expanding district heating networks, given their high efficiency and potential to integrate renewable and waste heat. However, these solutions will not be practical or cost-effective everywhere. For harder-to-treat buildings, such as homes currently using LPG or heating oil, properties unlikely to connect to heat (or hydrogen) networks, or buildings with low efficiency where deep renovation is difficult, renewable drop-in fuels can provide an additional decarbonisation route. In that context, rLG is best seen as a complementary option, helping decarbonise household heating where heat pumps or networks are not viable.

We consider three main groups of households to be relevant for future LPG or rLG demand:

- Households currently heating with LPG are assumed to remain on LPG unless they undertake a major renovation. We assume an energy renovation rate increasing from 1% to 2% by 2030, in line with current levels and EU objectives.<sup>1</sup> Renovated homes are likely to switch away from LPG to alternative low-carbon heating such as electrification via heat pumps. We have also considered efficiency gains of boiler replacement.<sup>2</sup>
- Households currently heating with oil may decide to switch to LPG if they are off-grid and not able to switch to a heat pump without substantial upgrades to the building. We estimate that this may affect 7.5 to 15% of currently oil-heated households.<sup>3</sup>
- Households currently heating with natural gas may equivalently decide to switch to LPG in cases where the gas grid is decommissioned and a switch to a heat pump is not

<sup>1</sup> <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0662>

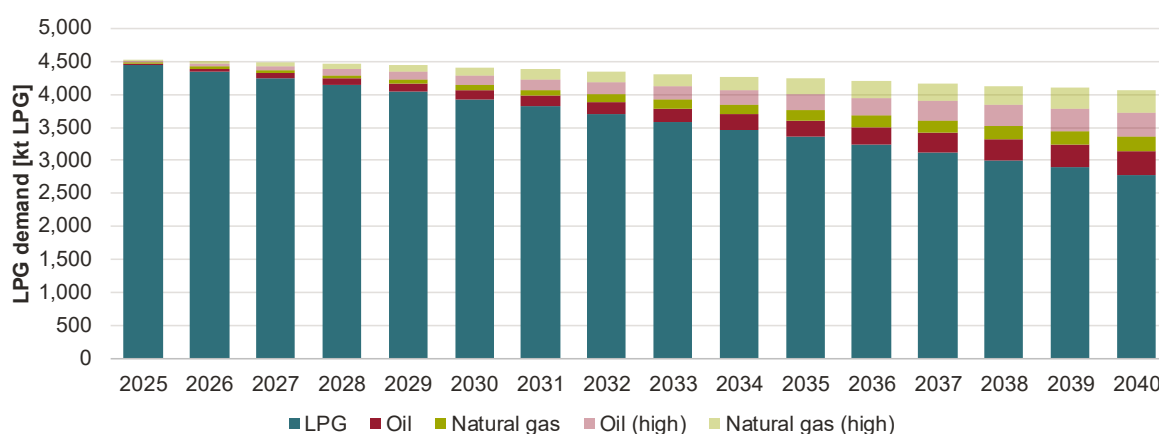
<sup>2</sup> We assume 30% efficiency gain from boiler replacement and an annual boiler replacement rate of around 4%.

<sup>3</sup> We estimate that around half of all oil-heated households in the EU 27+3 are off-grid, and 60% of oil-heated buildings would need significant building or system upgrades for heat pumps to operate efficiently. This is in line with a country-level estimate from Germany ([https://www.dvfg.de/fileadmin/user\\_upload/downloads/studien-gutachten/Fluessiggas-statt-Heizoel.pdf](https://www.dvfg.de/fileadmin/user_upload/downloads/studien-gutachten/Fluessiggas-statt-Heizoel.pdf)). We assume that one quarter to half of these households opts for LPG heating.

feasible. We estimate that this may affect 1 to 2.5% of households currently using natural gas for space heating.<sup>4</sup>

Based on the above, we derive an indication for an estimated total household LPG demand to 2040. As illustrated in Figure 1, total household LPG demand could decline by around 10 to 25% by 2040, relative to 2025. The majority of demand continues to come from households that are at present already using LPG for heating, but switching from oil and natural gas may lead to significant additional demand.

**Figure 1** Indication of potential household LPG demand to 2040



Source: Frontier Economics

Note: Shaded red and green areas indicate additional demand potential in a scenario with high switching to LPG.

## 1.2 Demand in other sectors

Across non-residential sectors, demand for conventional LPG is expected to trend down over time, driven by a mix of electrification, efficiency improvements and refinery throughput reductions. rLG can partially offset this decline in some applications, but is likely to be pulled first into harder-to-abate end uses where alternatives are limited or costly.

Demand for **autogas** is assumed to remain relatively stable in the short term, declining only slightly to around 95% of current demand by 2030. Beyond 2030, the outlook deteriorates more sharply as EU CO<sub>2</sub> reduction targets increasingly shape vehicle technology choices and fleet turnover, with demand falling to around 10% of current levels by 2050. Renewable liquid gases could slow the decline at the margin in segments where liquid fuels remain attractive

<sup>4</sup> We estimate that around 10% of all oil-heated households in the EU 27+3 are off-grid, and 60% of gas-heated buildings would need significant building or system upgrades for heat pumps to operate efficiently. We assume that one quarter to half of these households opts for LPG heating.

(for example in specific captive fleets), but are unlikely to reverse the structural shift away from fossil road fuels.

**Commercial** demand is expected to follow a similar trajectory to household demand, reflecting the same underlying drivers: improved building performance, a gradual shift to electrified heating solutions where feasible, and policy pressure to decarbonise heat. Renewable liquid gases may provide a niche decarbonisation option where electrification is constrained (for example due to site-specific limitations), but these applications are not expected to be large enough to materially change the overall downward trend.

LPG use in **refineries** is expected to fall materially as capacity declines in response to lower demand for refined products. We assume a linear reduction in refinery LPG use consistent with refinery capacity forecasts, reaching around 16% of current use by 2050.<sup>5</sup> While rLG could technically substitute for LPG in some refinery energy uses, the primary driver here is reduced refinery activity, which limits the scope for substitution to maintain volumes.

**Industrial** LPG demand is likely to decrease as electrification becomes viable for a growing share of industrial heat. As an indication of the potential scale, Fraunhofer ISI (2024) estimates suggest that around 62% of current industrial fuel demand could be replaced by electrification using technologies already available today, rising to around 90% from 2035 as additional technologies mature.<sup>6</sup> We treat these estimates as a stylised upper bound for the long-run reduction in industrial LPG use and test a sensitivity in which only half of this reduction is realised, recognising that today's LPG consumption is likely to be concentrated in relatively hard-to-electrify processes. In practice, residual demand is likely to persist in applications requiring high-temperature heat, operational flexibility, or where electrical grid constraints make electrification slow or expensive. These residual segments represent the most plausible use case for renewable liquid gases, which could act as a drop-in decarbonisation route where switching to electricity is not immediately practical.

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<sup>5</sup> S&P Global (2025), *Study on the potential evolution of Refining and Liquid Fuels production in Europe*, available at: <https://www.concawe.eu/wp-content/uploads/Study-on-the-potential-evolution-of-Refining-and-Liquid-Fuels-production-in-Europe-.pdf>

<sup>6</sup> Fraunhofer ISI (2024), *Direct electrification of industrial process heat. An assessment of technologies, potentials and future prospects for the EU*, available at: [https://www.agora-industry.org/fileadmin/Projects/2023/2023-20\\_IND\\_Electrification\\_Industrial\\_Heat/A-IND\\_329\\_04\\_Electrification\\_Industrial\\_Heat\\_WEB.pdf](https://www.agora-industry.org/fileadmin/Projects/2023/2023-20_IND_Electrification_Industrial_Heat/A-IND_329_04_Electrification_Industrial_Heat_WEB.pdf)

## 2 Economic viability of rLG

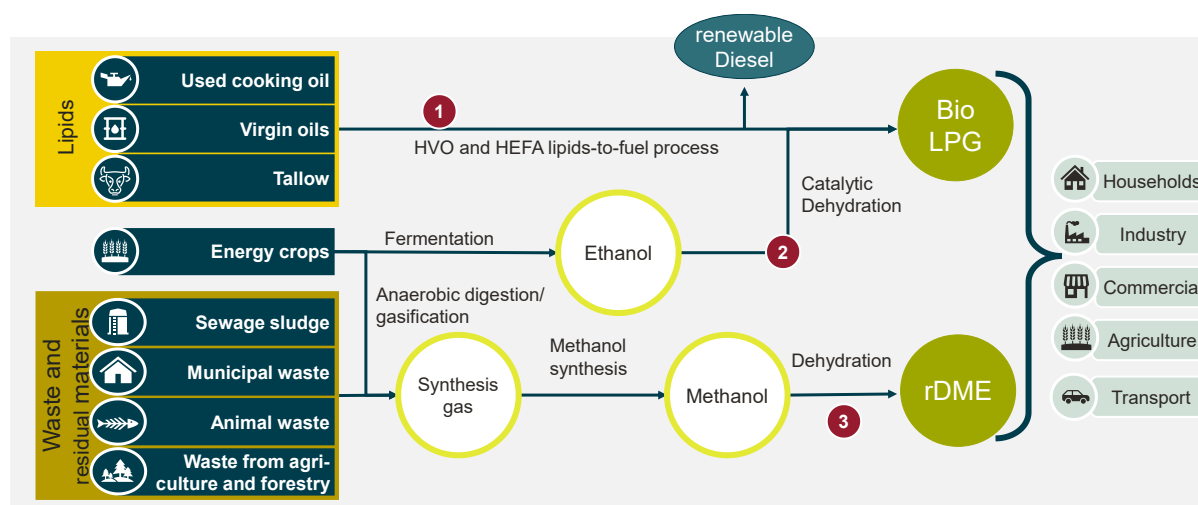
This annex describes the methodology used to derive country-specific LPG and rLG prices and to project their development to 2040. The approach ensures consistency across countries while preserving observed structural differences in taxation and distribution mark-ups.

### 2.1 Pathways considered

We focus on a selected set of rLG production pathways that are either already commercially available or at an advanced stage of development. The objective is to reflect a representative range of relevant rLG options, while ensuring that cost assumptions are grounded in sufficiently robust and transparent data.

Figure 2 provides an overview of the three pathways considered in this White Paper and their underlying feedstocks and conversion processes: bioLPG via HVO/HEFA, bioLPG via ethanol and bioDME.

**Figure 2** Focus pathways in this White Paper



Source: Frontier Economics

#### 2.1.1 bioLPG via HVO/HEFA

BioLPG produced via the HVO/HEFA pathway represents the most mature and commercially established renewable liquid gas option considered in this White Paper. In this pathway, bioLPG is generated as a by-product of the hydrotreated vegetable oil (HVO) and hydroprocessed esters and fatty acids (HEFA) process, which upgrades biogenic oils and fats into renewable diesel and aviation fuels.

The HVO/HEFA process is already deployed at scale across Europe, using feedstocks such as used cooking oil, animal fats, and other waste and residue lipids. As a result, bioLPG from

this route is already available on the market today, with observable wholesale prices and established supply chains. This makes it particularly suitable as a near-term decarbonisation option, as well as a robust reference point for cost analysis.

From a system perspective, the availability of bioLPG via HVO/HEFA is linked to the broader scale-up of renewable fuels for transport. While production volumes are therefore constrained by feedstock availability and follow demand for renewable diesel and SAF, the pathway benefits from high technical maturity and low deployment risk.

### **2.1.2 bioLPG via Ethanol**

BioLPG produced via the ethanol route is at an earlier stage of development but represents a clearly defined and scalable conversion pathway. In this process, bioethanol – produced from agricultural feedstocks or residues – is upgraded through catalytic dehydration and oligomerisation steps to yield LPG-range hydrocarbons.

In addition, the Ethanol-to-Jet (ETJ) pathway for the production of Sustainable Aviation Fuel (SAF) yields LPG-range hydrocarbons as a coproduct. As ETJ capacity scales up to meet aviation decarbonisation targets, associated bioLPG volumes are expected to increase in parallel. This creates an additional, policy-linked supply channel for bioLPG that is not primarily driven by LPG demand, but by SAF market developments.

While commercial-scale deployment remains limited, the underlying process steps are based on well-established technologies, and pilot and demonstration projects, like SHV Energy/GTI Energy project KatJa!, provide a basis for estimating yields and cost structures. This allows the pathway to be assessed using transparent, order of magnitude cost assumptions, despite its current lack of market maturity.

A key characteristic of the ethanol route is that production costs are largely driven by bioethanol feedstock prices, making the pathway sensitive to developments in agricultural markets and biofuel policies. Over time, however, the pathway could benefit from increasing availability of advanced and residue-based ethanol, as well as from learning effects as dedicated LPG-oriented upgrading facilities are deployed.

BioLPG via ethanol therefore represents a designated medium-term pathway, complementing the more mature HVO/HEFA route and contributing to diversification of rLG supply.

### **2.1.3 bioDME**

BioDME is produced using established methanol-to-DME synthesis processes, substituting fossil methanol with biomethanol derived from renewable feedstocks such as biomass or waste. This close alignment with existing industrial processes means that bioDME benefits from a high degree of technical maturity and process familiarity.

DME can be used directly as a fuel or blended with LPG, and it also functions as an effective hydrogen carrier, making it relevant beyond heating applications. The production pathway is particularly attractive from a scalability perspective, as it builds on existing methanol synthesis infrastructure and know-how.

Production costs for bioDME are primarily driven by the price of biomethanol. As renewable methanol production scales, bioDME costs are expected to decline. While current deployment remains limited, the pathway is well suited for medium- to long-term expansion.

In this White Paper, bioDME is included to capture an rLG option that combines technical maturity with longer-term cost reduction potential, thereby broadening the set of credible renewable liquid gas pathways considered.

### 2.1.4 Other pathways

Beyond the pathways assessed quantitatively in this White Paper, additional renewable liquid gas production routes could become relevant over the medium to longer term. In particular, electricity-based liquid gases (eDME and eLPG) represent an important future pathway.

eDME is produced using renewable electricity to generate hydrogen via electrolysis, which is then combined with captured CO<sub>2</sub> to produce renewable methanol and subsequently converted to DME. eLPG is also produced from renewable hydrogen and captured CO<sub>2</sub> but via a different process. These pathways offer very low life-cycle emissions and could play a role in a fully decarbonised energy system, particularly as renewable electricity becomes increasingly abundant and cost-competitive.

However, eDME production remains at an early stage of development and is currently still associated with relatively high costs, driven primarily by electricity prices, electrolysis costs, and CO<sub>2</sub> capture requirements. Cost projections depend on long-term developments in renewable power generation and hydrogen infrastructure.

Given the focus of this White Paper on short- to medium-term availability and economic viability, electricity-based DME is not included in the quantitative cost analysis. Nevertheless, it represents an important long-term complement to the bio-based pathways assessed here and could further expand the role of renewable liquid gases in a fully decarbonised energy system.

## 2.2 Country-specific LPG price forecasts take current prices as a starting point

For each country, we decompose today's observed retail LPG prices into the following components:

- European Wholesale price,
- Energy taxes (EnStG in Germany, Akcyza in Poland, Accisa in Italy),

- CO<sub>2</sub> levies (BEHG in Germany today),
- Value Added Tax (VAT), and
- Distribution, logistics and retail margin (residual mark-up on wholesale prices).

This is done both for prices at household and at industry level.

### 2.2.1 Price decomposition framework

As a first step, we use current country-specific end-user LPG prices as the starting point. From these prices, we deduct:

- Country-specific energy taxes (in absolute terms),
- Existing CO<sub>2</sub> levies, and
- Country-specific VAT (in relative terms).

This yields a country-specific supply price net of taxes and VAT. We then subtract a consistent wholesale price<sup>7</sup> from this supply price. The residual represents the country-specific mark-up covering distribution, logistics, and distributor/retailer margins.

This approach ensures that cross-country differences in retail prices are transparently attributed either to taxation or to structural differences in downstream cost and margin components.

### 2.2.2 Industry price adjustment

To reflect economies of scale and lower distribution costs for industrial consumers, we adjust the derived mark-up for industry prices. Specifically, the country-specific mark-up is reduced by 30% for industrial customers.

Other components are treated consistently with the retail framework. However, no VAT is applied to the industry prices.

### 2.2.3 Wholesale price projection

Wholesale LPG prices are projected using the Crude Oil price development from the World Energy Outlook (WEO) 2025, Net Zero Scenario.<sup>8</sup> We assume that LPG wholesale prices follow the same relative price trajectory as crude oil under this scenario. The resulting index is applied to the base-year (2025) LPG wholesale price to derive projected wholesale prices to 2040.

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<sup>7</sup> Consistent meaning that it's the same wholesale price for all three countries considered.

<sup>8</sup> International Energy Agency (2025): World Energy Outlook 2025. Available [here](#). [Accessed: March 2026]

This ensures internal consistency across countries, and alignment with a long-term decarbonisation pathway.

## 2.2.4 CO<sub>2</sub> pricing assumptions

From 2030 onwards, we apply consistent CO<sub>2</sub> pricing across all countries, based on:

- The expected introduction of the EU-ETS 2, and
- CO<sub>2</sub> price projections from the WEO 2025 (Net Zero Scenario)<sup>9</sup>.

This harmonised approach removes cross-country differences in carbon pricing assumptions beyond 2030 and ensures comparability in long-term projections.

Where national CO<sub>2</sub> schemes (BEHG in Germany) apply before 2030, these are reflected explicitly in the base-year price decomposition. Once EU-ETS 2 pricing is introduced, the national scheme (here: BEHG) is phased out and replaced by the harmonised EU carbon price assumption.

## 2.2.5 Treatment of taxes

We treat taxes as follows:

- Energy taxes (e.g. EnStG, Accisa, Akcyza) are held constant in absolute terms through 2040.
- VAT rates are held constant in relative (percentage) terms through 2040.

As wholesale prices evolve over time, VAT revenues change proportionally with the taxable base, while energy tax amounts remain fixed per unit.

This framework provides a transparent and internally consistent basis for cross-country comparison and long-term price projections. More detailed price components are presented in the data tables in annex chapter 5.

## 2.3 rLG prices are expected to decrease in the medium term

End-user prices for rLG are derived by applying a pathway-specific mark-up to the fossil LPG supply price (wholesale price plus country-specific mark-up), reflecting the higher production costs of renewable feedstocks. This mark-up is determined via wholesale price calculations of rLG. This differential is added consistently across countries, with analogous treatment of taxes and levies and no application of carbon pricing.<sup>10</sup>

<sup>9</sup> International Energy Agency (2025): World Energy Outlook 2025. Available [here](#). [Accessed: March 2026]

<sup>10</sup> By assumption, rLG pathways are exempt from carbon pricing.

### 2.3.1 BioLPG HVO/HEFA

BioLPG produced via the HVO/HEFA pathway is the most mature renewable liquid gas option and already commercially available. Cost estimates are therefore anchored in observed wholesale market prices, based on relevant price indices.

The BioLPG HVO/HEFA pathway is anchored in observed current BioLPG prices. For 2025, we use relevant wholesale price indices, corresponding to EUR 1,450 per tonne of LPG.<sup>11</sup> In combination with the detailed production cost assessment presented in Osipi et al. (2025)<sup>12</sup>, we derive a reasonable wholesale margin in absolute terms. This margin reflects capital recovery, operating costs and a commercial return. It is already embedded in the observed wholesale price and therefore not added separately.

To ensure consistency with the fossil LPG framework, we express the BioLPG wholesale price relative to the conventional LPG wholesale price. The difference between the two represents the BioLPG HVO/HEFA wholesale premium.

We deduct the conventional LPG wholesale price from the BioLPG wholesale price to derive the BioLPG HVO/HEFA mark-up over fossil LPG at wholesale level. This premium is then added to the country-specific LPG supply price derived in the main analysis. In doing so, we maintain the same structure for distribution and logistics mark-ups, energy taxes, and VAT treatment (in relative terms). The only exception concerns CO<sub>2</sub> levies, which are not applied to rLG prices.

Over time, bioLPG HVO/HEFA wholesale prices are projected to decline slightly. This reflects decreasing absolute wholesale margins as supply volumes scale up, modest reductions in operating costs linked to lower energy input prices and constant feedstock costs, reflecting continued competition for waste and residue oils.

Overall, bioLPG via HVO/HEFA represents a near-term rLG option with relatively stable and predictable costs – resulting prices are shown in Figure 3. More detailed price components are presented in the data tables in annex chapter 5.

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<sup>11</sup> Validated against, e.g., Argus biopropane fca ARA via [news item](#).

<sup>12</sup> Osipi, Sara Regina, Carlos Eduardo Korn Senko, and Mauro Antonio da Silva Sá Ravagnani (2025): Renewable propane and diesel production via used cooking oil hydroprocessing. *Energy Conversion and Management* 346: 120460.

**Figure 3 Price forecast for bioLPG via HVO/HEFA pathway**



Source: Frontier Economics

This methodology provides a transparent and internally consistent framework for integrating BioLPG (HVO/HEFA pathway) into the broader cross-country LPG price analysis.

### 2.3.2 BioLPG via Ethanol

BioLPG produced via ethanol conversion remains at an earlier stage of development, with cost evidence largely derived from pilot and demonstration projects. Production costs are primarily driven by the price of bioethanol feedstock.

For the 2025 cost estimate, we apply the following assumptions:

- BioLPG yield: 40.6%, based on documentation from Project KatJa!<sup>13</sup>,
- Bioethanol feedstock costs: Based on OECD-FAO Agricultural Outlook (2025) data for Europe<sup>14</sup>.
- Capital expenditure (CAPEX) and operating expenditure (OPEX): Estimated using high-level, order-of-magnitude benchmarks.

Using these inputs, we calculate the implied production cost per tonne of BioLPG. To ensure alignment with the HVO/HEFA methodology, we add the same wholesale margin (in absolute

<sup>13</sup> LiquidGas UK / SHV Energy (2022): Project KatJa! – On-Purpose BioLPG production from Ethanol, available [here](#).

<sup>14</sup> Via OECD [data explorer](#).

terms) as derived in the BioLPG HVO/HEFA analysis. This ensures consistent assumptions regarding commercial returns and market mark-ups across rLG pathways.

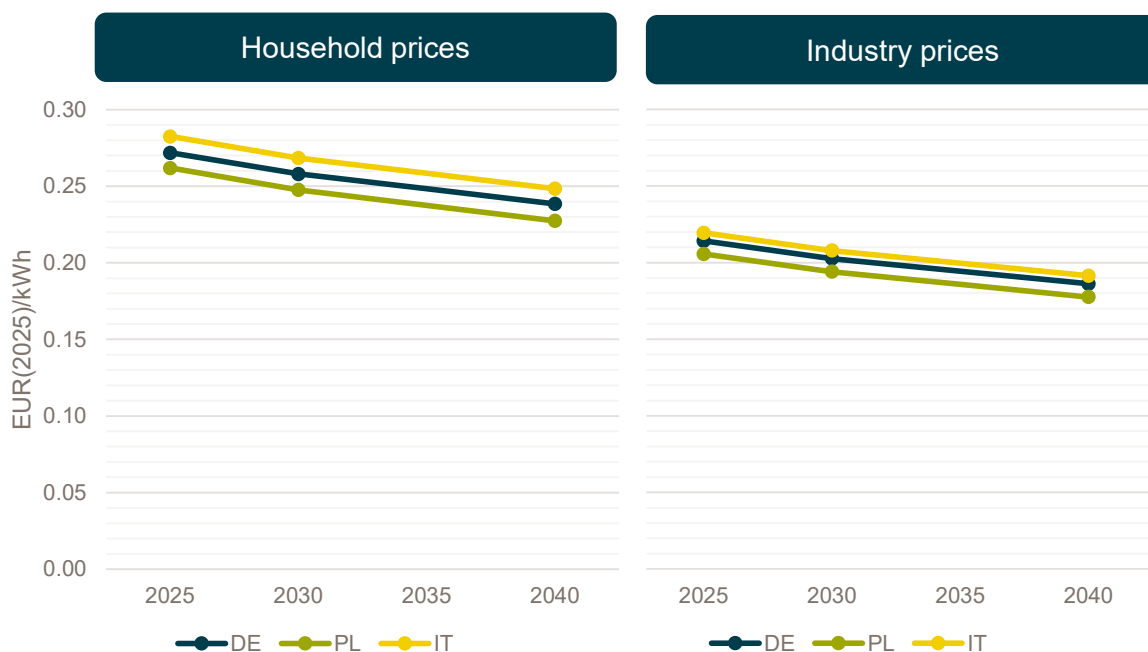
To maintain consistency with the fossil LPG pricing framework, we express the BioLPG Ethanol wholesale price relative to the conventional LPG wholesale price.

The resulting value represents the 2025 BioLPG Ethanol wholesale price. The difference between the two represents the BioLPG Ethanol wholesale premium. As for bioLPG HVO/HEFA, this premium is added to the country-specific LPG supply price derived in the main analysis (without carbon levies).

Future cost reductions are driven by slightly declining bioethanol prices, modest reductions in operating costs linked to energy prices, simplified learning-curve assumptions for capital expenditure, declining wholesale margins as market volumes increase.

Resulting prices are shown in Figure 4. While prices remain higher than for the HVO/HEFA route in the near term, the Ethanol pathway exhibits meaningful cost convergence over time. More detailed price components are presented in the data tables in annex chapter 5.

**Figure 4** Price forecast for bioLPG via Ethanol pathway



Source: Frontier Economics

This ensures a transparent and internally consistent integration of BioLPG via the ethanol route into the broader cross-country LPG and rLG price analysis framework.

### 2.3.3 bioDME

For **renewable DME**, we focus on **production routes based on biomethanol**, which closely mirror today's dominant methanol-to-DME processes. This allows us to rely on established process designs and documented project data.

Production costs are primarily driven by the cost of biomethanol feedstock. For the 2025 cost estimate, we apply the following assumptions:

- BioDME yield (**mass of final product vs feedstock**): 67.2%, based on Fortin et al. (2020)<sup>15</sup>,
- Biomethanol feedstock costs: Validated against a European Argus biomethanol price index<sup>16</sup>, assumed at EUR 1,000 per tonne,
- Capital expenditure (CAPEX) and operating expenditure (OPEX): Estimated based on the Fortin et al. (2020)<sup>17</sup> and, where relevant, expressed in annualised form.

Using these inputs, we calculate the implied production cost per tonne of BioDME.

To ensure consistency across rLG pathways, we add the same wholesale margin (in absolute terms) as applied in the BioLPG HVO/HEFA and Ethanol analysis. This ensures a harmonised assumption regarding commercial returns and wholesale mark-ups.

End-use prices for BioDME are derived using the same methodology as for the other rLG pathways. We express the BioDME wholesale price relative to the conventional LPG wholesale price. The difference between the two represents the BioDME wholesale premium which is added to the country-specific LPG supply price derived in the main analysis (without applying carbon levies).

Projected cost reductions are driven mainly by declining biomethanol feedstock costs, using published cost reduction profiles as a proxy. Other factors are slightly reduced energy-related operating costs and absolute wholesale margins that are assumed to decrease gradually as rLG market volumes expand and competition increases.

Price projections are shown in Figure 5. Overall, bioDME represents a technically mature rLG option with a clear pathway to cost reductions, particularly in scenarios with increased availability of low-cost renewable methanol. More detailed price components are presented in the data tables in annex chapter 5.

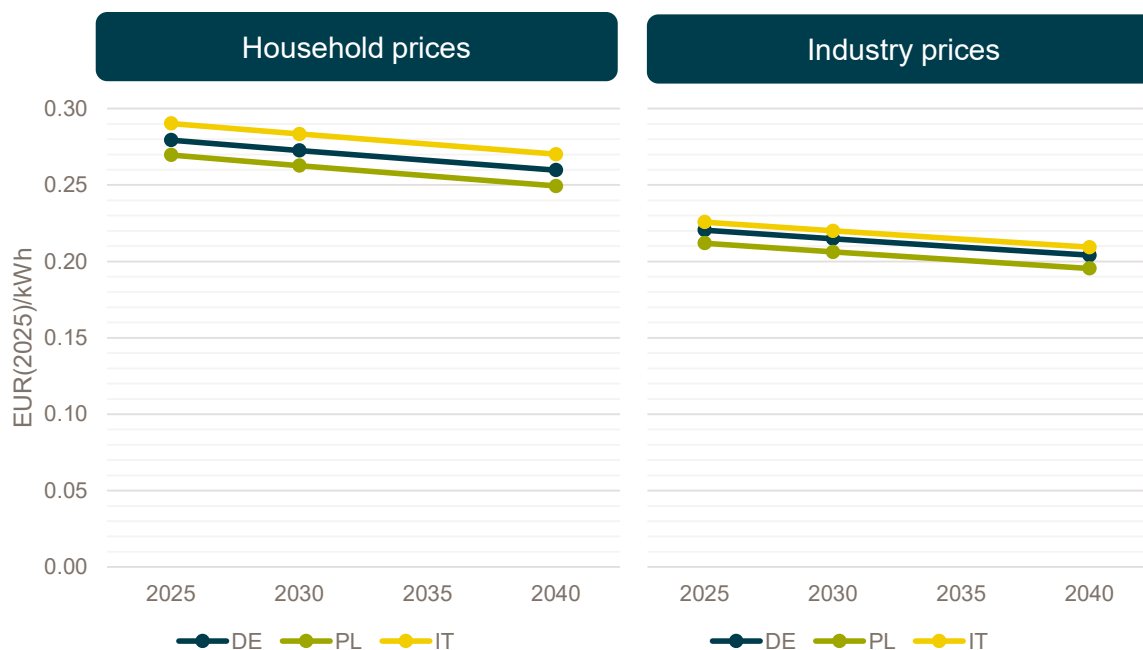
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<sup>15</sup> Fortin, Cyril, et al. (2020): Dimethyl ether, A review of production processes and a modeling of the indirect route. Liege Univ: 1-20. Available [here](#).

<sup>16</sup> Argus biomethanol fob Amsterdam-Rotterdam-Antwerp (ARA) via [news item](#).

<sup>17</sup> Fortin, Cyril, et al. (2020): Dimethyl ether, A review of production processes and a modeling of the indirect route. Liege Univ: 1-20. Available [here](#).

Figure 5 Price forecast for bioDME via Methanol



Source: Frontier Economics

This assessment does not capture the full range of potential renewable liquid gas production pathways. In practice, additional routes – most notably those based on renewable electricity – could deliver rLG at increasingly competitive costs over the longer term, with significant price reductions as technologies mature and scale. The focus of this White Paper is therefore not to provide an exhaustive overview of all rLG pathways, but to illustrate the diversity of available options and their short- to medium-term economic viability based on pathways that are already commercial or close to market deployment.

## 2.4 Methodology for calculating TCOs combines TABULA with When2Heat

**Total Cost of Ownership (TCO)** is a metric used to determine the overall cost of heating solutions. TCO includes the investment and installation costs of the respective heating technologies, relevant maintenance costs, and the costs of the required energy carriers for the reference buildings of choice.

More details on cost and price assumptions used as inputs to this analysis are presented in the data tables in annex chapter 5.

### 2.4.1 Reference buildings

For each country analysed, we selected a single-family home to serve as the reference building. Selection criteria were designed to ensure comparability across countries while reflecting national building characteristics. Specifically, reference buildings were chosen to:

- represent the single-family residential sector in each country;
- originate from a similar construction period;
- reflect a comparable renovation level consistent with national practice.

Building typology and characteristics were derived from the **TABULA webtool**<sup>18</sup> which has been developed within the framework of the Intelligent Energy Europe projects TABULA and EPISCOPE. It provides harmonised residential building archetypes across Europe. For each country, we identified the archetype that best matched our criteria in terms of construction era and renovation status. This ensured that reference buildings are broadly equivalent with regard to age and retrofit level, allowing consistent comparison of heating system performance, energy demand profiles, and cost metrics, while maintaining a country case study approach.

As a European project, each country building typology was set up by a national stakeholder. In our case this is

- Institute for Housing and Environment (IWU) for the German typology,
- National Energy Conservation Agency (NAPE) for the Polish typology, and
- Polytechnic University of Turin – Energy Department (POLITO) for the Italian typology.<sup>19</sup>

For each selected reference building, relevant parameters, floor area and annual heat demand, were extracted directly from TABULA. These parameters form the basis for subsequent modelling of peak load, annual energy demand, and technology sizing in the Total Cost of Ownership analysis.

## 2.4.2 Investment and installation costs

Investment costs depend primarily on the size of the heating system. For the building types considered, heating capacity is determined based on the expected peak thermal demand. Peak thermal demand is modelled using country-specific thermal demand profiles for single-family homes from the **When2Heat dataset** for the 2019 heating year.<sup>20</sup> These profiles are scaled to the building's annual heat demand as reported in TABULA.

We model heat pumps with a high flow temperature (due to heat distribution via radiator in the reference buildings) and bivalent operation. Systems are sized to cover 95% of peak thermal demand. The highest 5% of peak thermal demand are covered by an electric heating rod.

<sup>18</sup> Available via <https://webtool.building-typology.eu/#bm>.

<sup>19</sup> More details via <https://webtool.building-typology.eu/#bm>, "About" section.

<sup>20</sup> Available via <https://data.open-power-system-data.org/when2heat/>. This dataset is based on Ruhnau, O., Hirth, L., and Praktiknjo, A. (2019). Time series of heat demand and heat pump efficiency for energy system modeling. *Scientific Data*, 6, 189. <https://doi.org/10.1038/s41597-019-0199-y>. Ruhnau, O., Muessel, J. (2023). Update and extension of the When2Heat dataset. *Econstor Working Paper*. <http://hdl.handle.net/10419/249997>. Ruhnau, O., Muessel, J. (2023). When2Heat Heating Profiles. *Open Power System Data*. <https://doi.org/10.25832/when2heat/2023-07-27>.

Although the heating rod operates at lower efficiency than the heat pump, this assumption significantly reduces the required heat pump capacity and, therefore, investment costs.

All relevant installation costs are included. We do not account for investment subsidies or preferential support schemes.

The investment and installation costs derived from system size are converted into annuities over the technical lifetime of the systems within the TCO framework. This annuity approach allows annual TCO to be calculated.

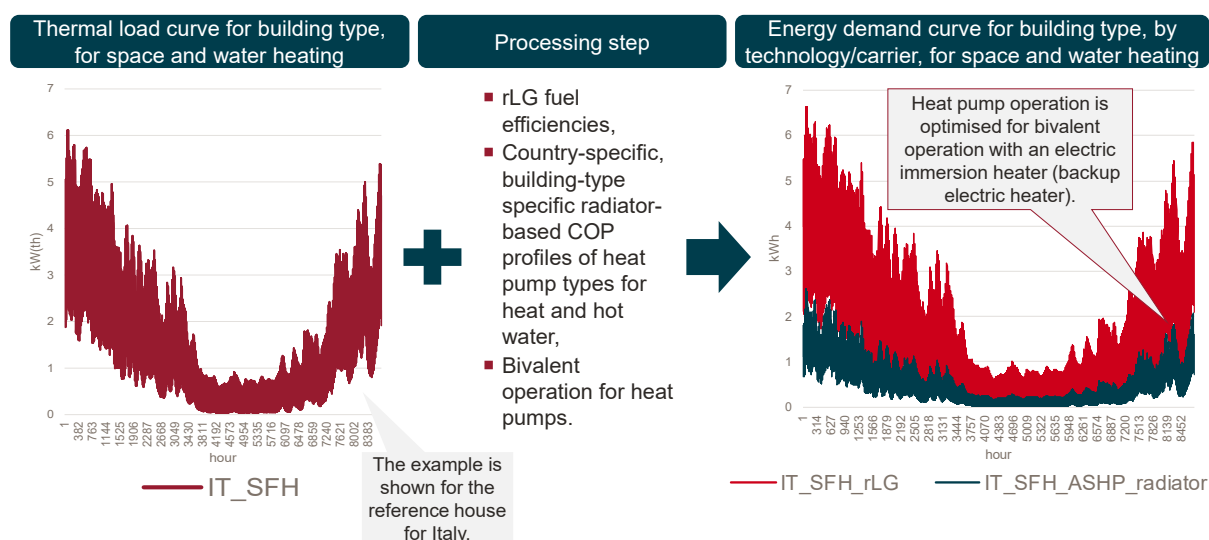
### 2.4.3 Maintenance costs

Maintenance costs are treated as expected annual costs and are directly incorporated into the annual TCO calculation.

### 2.4.4 Energy carrier costs

Annual energy carrier costs are calculated by multiplying the carrier prices by the energy carrier demand. The demand is calculated from the thermal heat demand curve of the relevant building, combined with technology-specific fuel efficiencies, coefficients of performance and heat pump sizing considerations for bivalent operation. For heat pumps, country-specific hourly coefficients of performance are taken directly from the When2Heat dataset.<sup>21</sup>

**Figure 6 Processing the thermal demand curve into technology-specific energy demand**



<sup>21</sup> For radiator-based systems, the average annual COP of an air-source heat pump (ASHP) is 3.5 in Germany and Poland, and 3.6 in Italy. Using a ground-source heat pump (GSHP) increases the average COP to between 4.9 and 5.1, depending on the country, but entails higher upfront investment costs. As noted in the main text, the overall cost conclusions do not differ materially between ASHP and GSHP configurations.

Source: *Frontier Economics, based on When2Heat thermal demand and COP profiles and TABULA reference buildings.*

Energy carrier costs are estimated based on the current state of research and available forward prices for the relevant years 2025, 2030 and 2040.

For LPG and rLG, we rely on the prices presented in previous chapter.

For electricity, we use actual 2025 household prices for all countries, inclusive of all applicable taxes and levies. We do not apply heat pump–specific tariffs or any other tariff exemptions. The analysis is designed as an economic assessment that abstracts from subsidies.

For the German electricity prices, we forecast and interpolate household electricity prices based on:

- Forecasts of the household electricity base price based on Ariadne (2025)<sup>22</sup>, and
- Separate forecasts of network charges by Consentec/Frontier Economics (2025)<sup>23</sup>.

For Poland and Italy, we apply the same price development as in Germany as of 2025 as a simplifying assumption. We validate this assumption against separate, country-specific LCOE forecasts for both countries.

For all energy carriers, price developments are forecasted until 2050, and are kept constant after that.

## 2.5 Sensitivities TCO calculation

As an illustrative example, we present sensitivities for a selection of the same buildings considered in our reference case, but assuming different renovation levels (one with improved insulation and one with poorer insulation). Renovation costs are not accounted for in the TCO calculation.


For the German reference building, we show the TCO calculation under a higher renovation standard (equivalent to “ambitious refurbishment” in TABULA). Please note that the TCO results are based on a different heat pump specification. The improved building envelope is assumed to enable heat distribution via underfloor heating, which increases heat pump efficiency by allowing lower flow temperatures. The results are presented in Figure 7. TCO

<sup>22</sup> Gunnar Luderer (Hrsg.), Frederike Bartels (Hrsg.), Tom Brown (Hrsg.), Clara Aulich, Falk Benke, Tobias Fleiter, Fabio Frank, Helen Ganal, Julian Geis, Norman Gerhardt, Till Gnann, Alyssa Gunnemann, Robin Hasse, Andrea Herbst, Sebastian Herkel, Johanna Hoppe, Christoph Kost, Michael Krail, Michael Lindner, Marius Neuwirth, Hannah Nolte, Robert Pietzcker, Patrick Plötz, Matthias Rehfeldt, Felix Schreyer, Toni Seibold, Charlotte Senkpiel, Dominika Sörgel, Daniel Speth, Bjarne Steffen, Philipp C. Verpoort (2025): Die Energiewende kosteneffizient gestalten: Szenarien zur Klimaneutralität 2045. Kopernikus-Projekt Ariadne, Potsdam. <https://doi.org/10.48485/pik.2025.003>. Available [here](#).

<sup>23</sup> Consentec and Frontier Economics for BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. (2025): Prognose und Analyse der Netzentgeltentwicklung. Available [here](#).

decrease by between one third and one half, relative to the standard insulation level results presented in the main report.

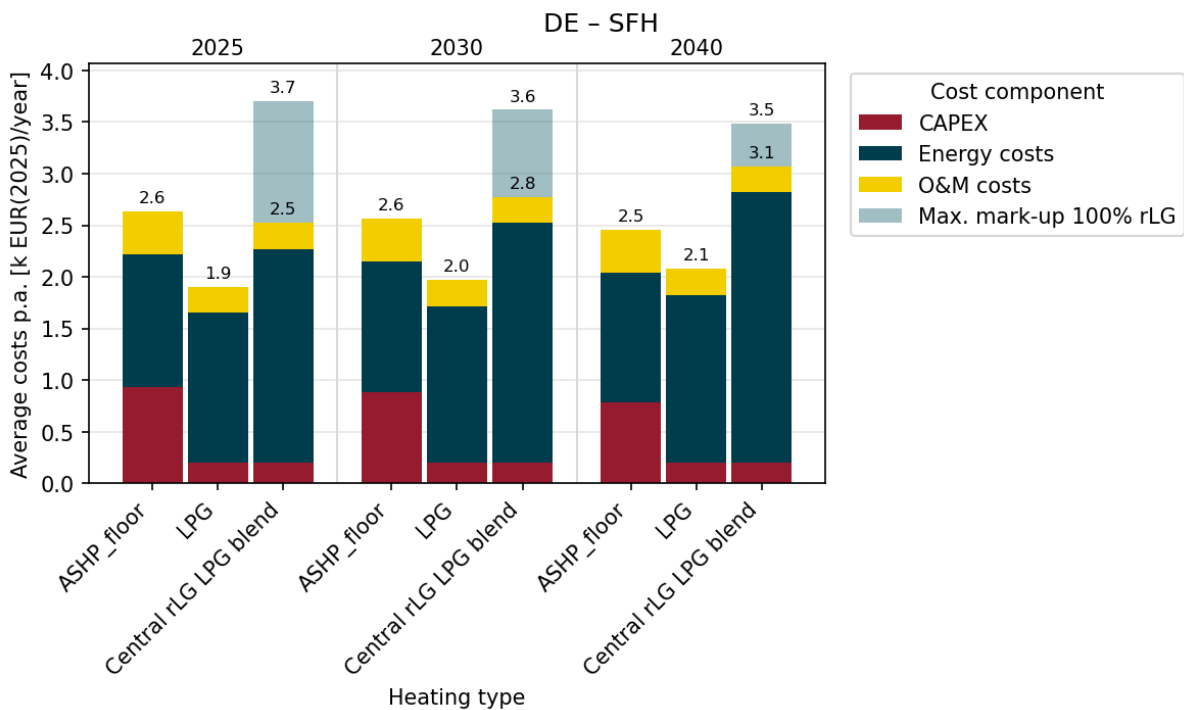
**Figure 7 Sensitivity: Above average energy performance – German reference house and associated heating TCO**



Representative **German single-family house** constructed **between 1958 and 1968**, assuming an **above average renovation rate\***.

Reference floor area of **121 m<sup>2</sup>**, with

- a thermal demand for space heating of **72.5 kWh(th)/m<sup>2</sup>**, and
- a thermal demand for domestic hot water of **800 kWh(th)** per person (for 3 persons).



Source: Frontier Economics, building information / picture via TABULA.


Note: Costs shown represent annualised capital expenditure as well as average energy and operation and maintenance costs per year, assuming a heating technology lifetime of 20 years starting in the indicated year of investment. The detailed calculation methodology is set out in the technical annex of this White Paper. The analysis draws primarily on the open-source datasets When2Heat and the TABULA building typology, complemented by assumptions on relevant cost structures. The “max. mark-up 100% rLG” represents the additional cost required to move from the central blend to the most expensive rLG pathway in our analysis (bioDME).

ASHP\_radiator: Air-source heat pump with radiator-based heat distribution.

\* Equals energy performance level 3 (“ambitious refurbishment”) in TABULA.

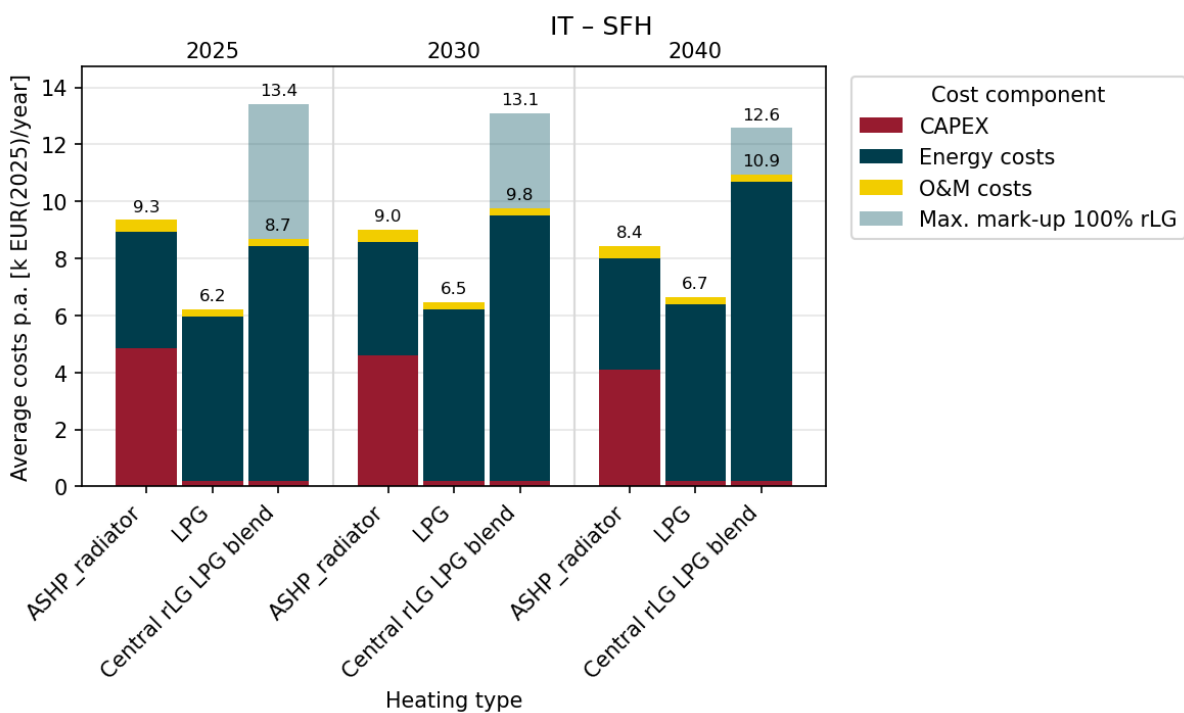
To illustrate the impact of poorer insulation, we present the Italian reference building in its original condition at the time of construction (“existing state” in TABULA). Under this assumption, TCO increase substantially – by almost a factor of three – compared to the case with average insulation levels presented in the main report. However, the relative competitiveness of the different heating technologies at TCO level remains largely unchanged.

**Figure 8 Sensitivity: Below average energy performance – Italian reference house and associated heating TCO**



Representative **Italian single-family house** constructed **between 1946 and 1960**, assuming a **below average renovation rate\***.  
 Reference floor area of **162 m<sup>2</sup>**, with

- a thermal demand for space heating of **250.3 kWh(th)/m<sup>2</sup>**, and
- a thermal demand for domestic hot water of **800 kWh(th)** per person (for 3 persons).



Source: Frontier Economics, building information / picture via TABULA.

Note: Costs shown represent annualised capital expenditure as well as average energy and operation and maintenance costs per year, assuming a heating technology lifetime of 20 years starting in the indicated year of investment. The detailed calculation methodology is set out in the technical annex of this White Paper. The analysis draws primarily on the open-source datasets When2Heat and the TABULA building typology, complemented by assumptions on relevant cost structures. The “max. mark-up 100% rLG” represents the additional cost required to move from the central blend to the most expensive rLG pathway in our analysis (bioDME).

ASHP\_radiator: Air-source heat pump with radiator-based heat distribution.

\* Equals energy performance level 1 (“existing state”) in TABULA.

## 2.6 Inputs and references for application-level cost comparison of industrial heating processes

We assess the relative economics of electrification against a benchmark fossil LPG application as well as an rLG application as an alternative decarbonisation route. For this purpose, we use specific energy consumption and investment cost data from published studies and available pilot project reports in combination with our own forecasts for electricity and LPG prices, as presented in the data tables in annex chapter 5. Table 1 summarises the relevant inputs, references and assumptions for our analysis.

**Table 1 Inputs and references for application-level cost comparison of industrial heating processes**

|  | Brick firing  | Asphalt                         | Aluminium                       | Distilleries                    |
|--|---|---------------------------------|---------------------------------|---------------------------------|
| Specific energy consumption natural gas / LPG <sup>a</sup> | 0.525 MWh/t <sup>b</sup>  | 0.082 MWh/t <sup>c</sup>        | 0.74 MWh/t <sup>b</sup>         | 0.010 MWh/l <sup>d</sup>        |
| Specific energy consumption electrification                | 0.499 MWh/t <sup>b</sup>  | 0.091 MWh/t <sup>c</sup>        | 0.64 MWh/t <sup>b</sup>         | 0.002 MWh/l <sup>d</sup>        |
| CAPEX for electrification retrofit                         | 161 EUR/t capacity <sup>b</sup>                                 | 51 EUR/t capacity <sup>c</sup>  | 7.7 EUR/t capacity <sup>b</sup> | 1.5 EUR/l <sup>d</sup>          |
| Plant capacity   | 28,000 t/a <sup>b</sup>   | n/a                             | 30,000 t/a <sup>b</sup>         | 676,000 l/a <sup>e</sup>        |
| O&M cost electrification                                   | 32.1 EUR/t capacity <sup>b</sup>                                | 5.1 EUR/t capacity <sup>f</sup> | 0.1 EUR/t capacity <sup>b</sup> | 0.1 EUR/l capacity <sup>f</sup> |
| O&M cost LPG/rLG   | 32.1 EUR/t capacity <sup>b</sup>                                | 5.1 EUR/t capacity <sup>f</sup> | 7.7 EUR/t capacity <sup>b</sup> | 0.1 EUR/l capacity <sup>f</sup> |
| Electricity prices   |   |                                 |                                 |                                 |
| LPG prices   | Frontier Economics forecasts on electricity, LPG and rLG prices |                                 |                                 |                                 |
| rLG prices   |   |                                 |                                 |                                 |

Source: Frontier Economics

Note: a – In the absence of robust process-specific LPG data, we assume LPG has the same specific energy consumption as natural gas for the relevant applications.

b – UBA (2023)

c – Oliveira & Silva (2022)

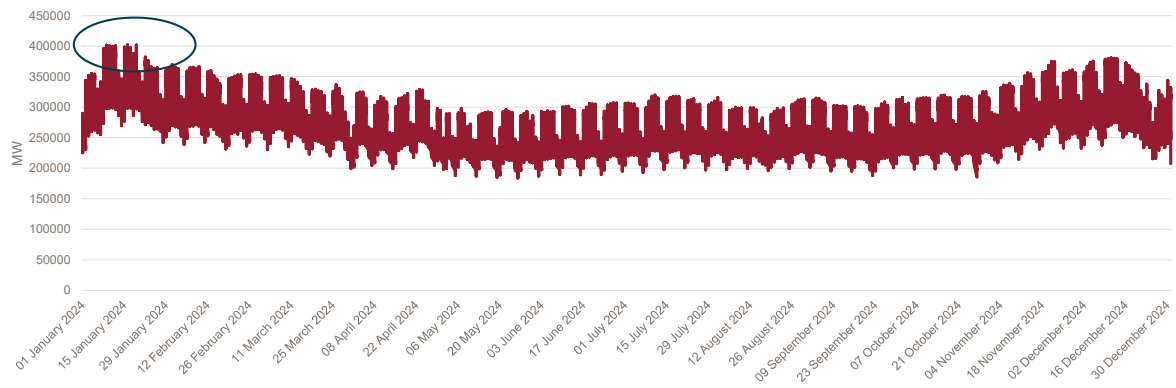
d – IEA HPT TCP (n.d.)

e – Distillery is producing 13 casks of 200l per day, 5 days a week all year round (<https://ahascraghdistillery.com>).

f – O&M cost is assumed to amount to 10% of CAPEX for electrification retrofit.

### 3 System Implications and Comparative Assessment

Figure 9 Hourly electricity demand in EU27+UK+NO+CH in 2024



Source: Frontier Economics based on ENTSO-E Power Statistics

## 4 Emissions impact of rLG

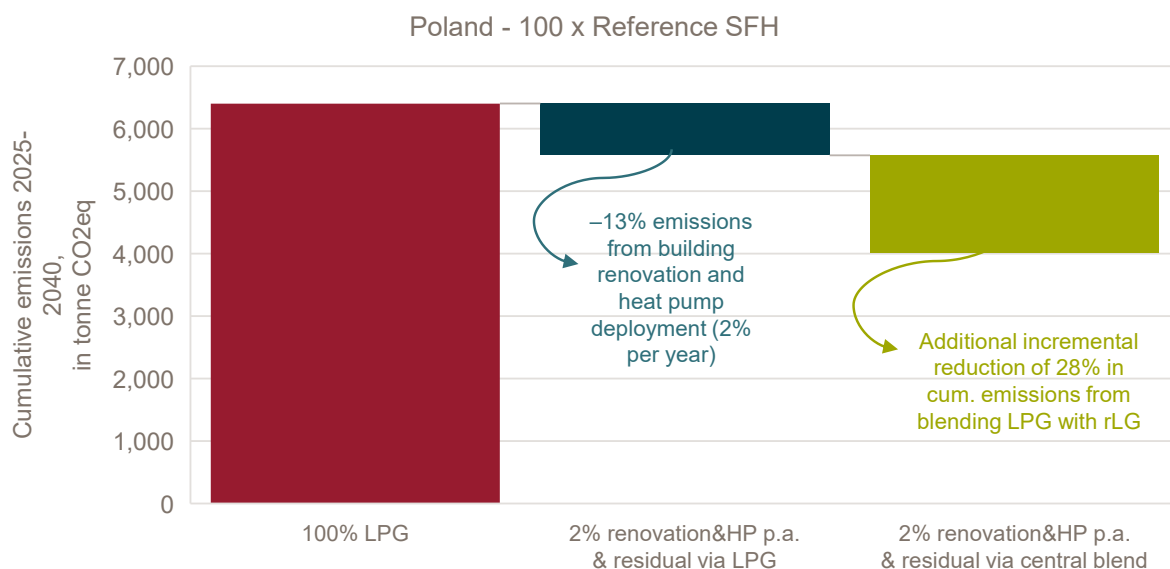
The results for the Polish and Italian illustrative housing district consisting of 100 identical reference single-family homes confirm the core finding from Germany. Under a stylised pathway with 2% annual renovation and heat pump deployment, cumulative emissions over 2025–2040 fall by around 13–14% compared to a fossil LPG baseline.

Introducing rLG blending for the remaining LPG users materially increases emission reductions. Compared to heat pump uptake alone, cumulative emissions decline by a further 28%, when assuming the reference central blend.

As in Germany, combining gradual electrification with rLG blending substantially accelerates emissions reductions relative to relying on heat pump uptake alone.

Country results are shown in Figure 10 and Figure 11.

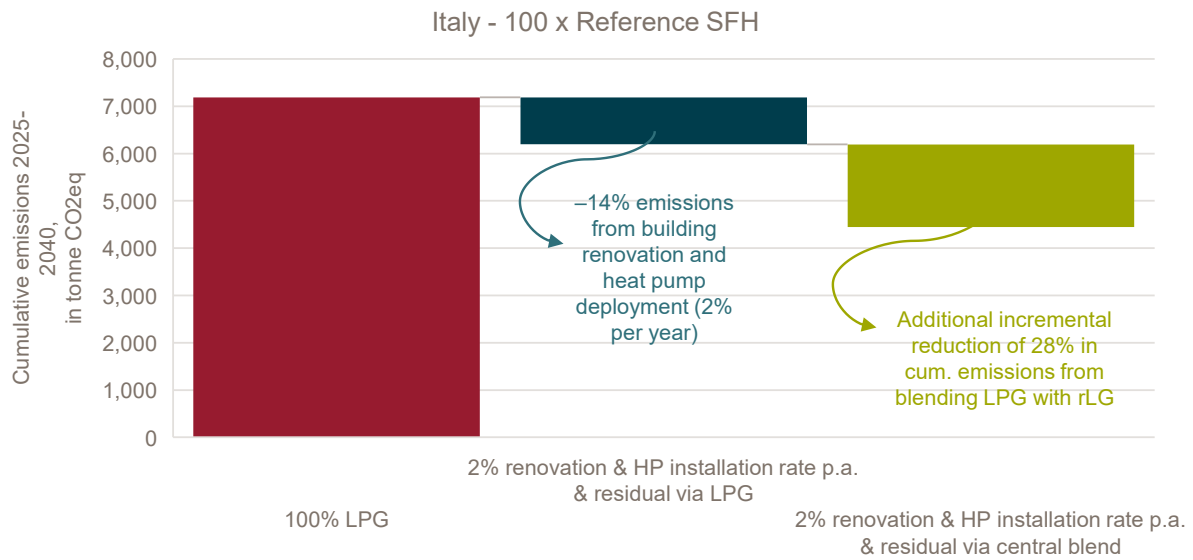
**Figure 10 Cumulative emissions and emission reductions 2025-2040 at Polish reference building level**



Source: Frontier Economics

Note: In this assessment, renovated buildings are assumed to have improved insulation (i.e. lower energy demand) and to use an air-source heat pump (ASHP) with underfloor heating.

**Figure 11 Cumulative emissions and emission reductions 2025-2040 at Italian reference building level**



Source: Frontier Economics

Note: In this assessment, renovated buildings are assumed to have improved insulation (i.e. lower energy demand) and to use an air-source heat pump (ASHP) with underfloor heating.

## 5 Data tables

### 5.1 LPG prices

#### 5.1.1 Germany

| <b>Germany LPG prices</b> | <b>unit</b>     | <b>2025</b> | <b>2030</b> | <b>2040</b> |
|---------------------------|-----------------|-------------|-------------|-------------|
| Wholesale price           | EUR(2025)/tonne | 383         | 270         | 156         |
| National supply price     | EUR(2025)/tonne | 995         | 881         | 768         |
| CO2 levies                | EUR(2025)/tonne | 166         | 271         | 534         |
| Energy tax                | EUR(2025)/tonne | 61          | 61          | 61          |
| VAT 19%                   | EUR(2025)/tonne | 232         | 230         | 259         |
| <b>Household price</b>    |                 |             |             |             |
| Total                     | EUR(2025)/tonne | 1453        | 1443        | 1621        |
|                           | EUR(2025)/kWh   | 0.11        | 0.11        | 0.13        |
| <b>Industry price</b>     |                 |             |             |             |
| Total                     | EUR(2025)/tonne | 1037        | 1029        | 1179        |
|                           | EUR(2025)/kWh   | 0.08        | 0.08        | 0.09        |

Current household prices via [Flüssiggas1](#) and [Energieverbraucher](#). Current wholesale price LPG assumed at 450 \$/tonne via [Argus CIF ARA](#), forecasted with [WEO 2025, Net Zero scenario](#), relative price development for natural gas. Carbon levies as of 2030 via carbon price forecasts from [WEO 2025, Net Zero scenario](#).

## 5.1.2 Poland

| <b>Poland LPG prices</b> | <b>unit</b>     | <b>2025</b> | <b>2030</b> | <b>2040</b> |
|--------------------------|-----------------|-------------|-------------|-------------|
| Wholesale price          | EUR(2025)/tonne | 383         | 270         | 156         |
| National supply price    | EUR(2025)/tonne | 698         | 584         | 471         |
| CO2 levies               | EUR(2025)/tonne | 0           | 271         | 534         |
| Akcyza                   | EUR(2025)/tonne | 158         | 158         | 158         |
| VAT 23%                  | EUR(2025)/tonne | 197         | 233         | 267         |
| <b>Household price</b>   |                 |             |             |             |
| Total                    | EUR(2025)/tonne | 1053        | 1246        | 1430        |
|                          | EUR(2025)/kWh   | 0.08        | 0.10        | 0.11        |
| <b>Industry price</b>    |                 |             |             |             |
| Total                    | EUR(2025)/tonne | 761         | 919         | 1068        |
|                          | EUR(2025)/kWh   | 0.06        | 0.07        | 0.08        |

Current household prices via [Cdc24](#), Akcyza via [Podatki](#). Current wholesale price LPG assumed at 450 \$/tonne via [Argus CIF ARA](#), forecasted with [WEO 2025, Net Zero scenario](#), relative price development for natural gas. Carbon levies as of 2030 via carbon price forecasts from [WEO 2025, Net Zero scenario](#).

### 5.1.3 Italy

| <b>Italy LPG prices</b> | <b>unit</b>     | <b>2025</b> | <b>2030</b> | <b>2040</b> |
|-------------------------|-----------------|-------------|-------------|-------------|
| Wholesale price         | EUR(2025)/tonne | 383         | 270         | 156         |
| National supply price   | EUR(2025)/tonne | 907         | 793         | 680         |
| CO2 levies              | EUR(2025)/tonne |             | 271         | 534         |
| Accisa                  | EUR(2025)/tonne | 190         | 190         | 190         |
| VAT 22%                 | EUR(2025)/tonne | 241         | 276         | 309         |
| <b>Household price</b>  |                 |             |             |             |
| Total                   | EUR(2025)/tonne | 1338        | 1530        | 1712        |
|                         | EUR(2025)/kWh   | 0.10        | 0.12        | 0.13        |
| <b>Industry price</b>   |                 |             |             |             |
| Total                   | EUR(2025)/tonne | 939         | 1097        | 1246        |
|                         | EUR(2025)/kWh   | 0.07        | 0.09        | 0.10        |

Current household prices via [Fuelo](#), reduced for Accisa “usa carburazione” to “uso riscaldamento” via [ADM](#). Current wholesale price LPG assumed at 450 \$/tonne via [Argus CIF ARA](#), forecasted with [WEO 2025, Net Zero scenario](#), relative price development for natural gas. Carbon levies as of 2030 via carbon price forecasts from [WEO 2025, Net Zero scenario](#).

## 5.2 rLG prices

### 5.2.1 bioLPG HVO/HEFA

| <b>bioLPG HVO/HEFA – Wholesale prices</b>  |  | <b>unit</b>            | <b>2025</b>  | <b>2030</b>  | <b>2040</b>  |
|--|--|------------------------|--------------|--------------|--------------|
| Production cost                            |  | EUR(2025)/tonne        | 1,313        | 1,293        | 1,273        |
| of which annualis. capital costs           |  | EUR(2025)/tonne        | 34           | 34           | 34           |
| of which operating costs (incl. feedstock) |  | EUR(2025)/tonne        | 1,279        | 1,259        | 1,239        |
| Assumed margin                             |  | EUR(2025)/tonne        | 137          | 120          | 100          |
| <b>Total wholesale price</b>               |  | <b>EUR(2025)/tonne</b> | <b>1,450</b> | <b>1,413</b> | <b>1,373</b> |
| <b>Household prices</b>                    |  | <b>unit</b>            | <b>2025</b>  | <b>2030</b>  | <b>2040</b>  |
| DE   |  | EUR(2025)/tonne        | 2,526        | 2,482        | 2,434        |
|  |  | EUR(2025)/kWh          | 0.20         | 0.19         | 0.19         |
| PL   |  | EUR(2025)/tonne        | 2,365        | 2,320        | 2,270        |
|  |  | EUR(2025)/kWh          | 0.18         | 0.18         | 0.18         |
| IT   |  | EUR(2025)/tonne        | 2,639        | 2,595        | 2,545        |
|  |  | EUR(2025)/kWh          | 0.20         | 0.20         | 0.20         |
| <b>Industry prices</b>                     |  | <b>unit</b>            | <b>2025</b>  | <b>2030</b>  | <b>2040</b>  |
| DE   |  | EUR(2025)/tonne        | 1,939        | 1,902        | 1,861        |
|  |  | EUR(2025)/kWh          | 0.15         | 0.15         | 0.14         |
| PL   |  | EUR(2025)/tonne        | 1,828        | 1,792        | 1,751        |
|  |  | EUR(2025)/kWh          | 0.14         | 0.14         | 0.14         |
| IT   |  | EUR(2025)/tonne        | 2,006        | 1,970        | 1,929        |
|  |  | EUR(2025)/kWh          | 0.16         | 0.15         | 0.15         |

Argus/Platts commodity prices for 2025 wholesale<sup>24</sup>, current wholesale margin derived via Osipi et al. (2025)<sup>25</sup>. Cost reductions are driven by the assumption of a slight decline of the rLG wholesale margin over time and a gradual decrease in the energy-cost share of operating costs. Feed oil prices are assumed to be constant. The relevant cost share is based on Osipi et al. (2025)<sup>26</sup>, forecasted with the proxy of electricity price development Net Zero scenario via WEO 2025<sup>27</sup>. The wholesale price premium of bioLPG (HVO/HEFA) relative to conventional LPG is added to the respective national LPG supply price (both at household and at industry level). Relevant additional price components, including energy taxes and applicable VAT which are detailed in Chapter 5.1, are then applied.

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<sup>24</sup> Validated against, e.g., Argus biopropane fca ARA via [news item](#).

<sup>25</sup> Based on a medium-capacity plant from Osipi, Sara Regina, Carlos Eduardo Korn Senko, and Mauro Antonio da Silva Sá Ravagnani (2025): Renewable propane and diesel production via used cooking oil hydroprocessing. Energy Conversion and Management 346: 120460. This includes capital costs of 54.8 million \$(2025) for an annual plant output of 162k tonnes renewable diesel and 10.8k tonnes renewable LPG.

<sup>26</sup> Osipi, Sara Regina, Carlos Eduardo Korn Senko, and Mauro Antonio da Silva Sá Ravagnani (2025): Renewable propane and diesel production via used cooking oil hydroprocessing. Energy Conversion and Management 346: 120460.

<sup>27</sup> International Energy Agency (2025): World Energy Outlook 2025. Available [here](#).

## 5.2.2 bioLPG Ethanol

| <b>bioLPG Ethanol – Wholesale prices</b>   |  | <b>unit</b>            | <b>2025</b>  | <b>2030</b>  | <b>2040</b>  |
|--|--|------------------------|--------------|--------------|--------------|
| Production cost                            |  | EUR(2025)/tonne        | 2,133        | 2,001        | 1,809        |
| of which annualis. capital costs           |  | EUR(2025)/tonne        | 90           | 76           | 63           |
| of which operating costs (incl. feedstock) |  | EUR(2025)/tonne        | 2,043        | 1,924        | 1,746        |
| Assumed margin                             |  | EUR(2025)/tonne        | 137          | 120          | 100          |
| <b>Total wholesale price</b>               |  | <b>EUR(2025)/tonne</b> | <b>2,270</b> | <b>2,121</b> | <b>1,909</b> |
| <b>Household prices</b>                    |  |                        |              |              |              |
|  |  | <b>unit</b>            | <b>2025</b>  | <b>2030</b>  | <b>2040</b>  |
| DE   |  | EUR(2025)/tonne        | 3,501        | 3,324        | 3,071        |
|  |  | EUR(2025)/kWh          | 0.27         | 0.26         | 0.24         |
| PL   |  | EUR(2025)/tonne        | 3,373        | 3,190        | 2,929        |
|  |  | EUR(2025)/kWh          | 0.26         | 0.25         | 0.23         |
| IT   |  | EUR(2025)/tonne        | 3,639        | 3,458        | 3,199        |
|  |  | EUR(2025)/kWh          | 0.28         | 0.27         | 0.25         |
| <b>Industry prices</b>                     |  |                        |              |              |              |
|  |  | <b>unit</b>            | <b>2025</b>  | <b>2030</b>  | <b>2040</b>  |
| DE   |  | EUR(2025)/tonne        | 2,648        | 2,499        | 2,287        |
|  |  | EUR(2025)/kWh          | 0.21         | 0.20         | 0.19         |
| PL   |  | EUR(2025)/tonne        | 2,758        | 2,610        | 2,398        |
|  |  | EUR(2025)/kWh          | 0.21         | 0.19         | 0.18         |
| IT   |  | EUR(2025)/tonne        | 2,826        | 2,677        | 2,465        |
|  |  | EUR(2025)/kWh          | 0.22         | 0.21         | 0.19         |

European Ethanol prices via OECD-FAO Agricultural Outlook 2025-2034<sup>28</sup> combined with a propane/butane yield of 40.6% observed in Project KatJa!<sup>29</sup>. We apply order-of-magnitude assumptions for both capital and operating costs.<sup>30</sup> Capital costs decline over time in line with assumed learning curve effects, while operating costs decrease slightly due to modest reductions in energy costs (proxied by electricity price development Net Zero scenario via WEO 2025<sup>31</sup>). The wholesale margin, in absolute terms, is assumed to be equal to that of bioLPG (HVO/HEFA) and to follow the same rate of reduction over time. The wholesale price premium of bioLPG (Ethanol) relative to conventional LPG is added to the respective national LPG supply price (both at household and at industry level). Relevant additional price components, including energy taxes and applicable VAT, which are detailed in Chapter 5.1, are then applied.

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<sup>28</sup> OECD-FAO (2025): Agricultural Outlook 2025-2034, via [data explorer](#). Values have been deflated with a 2% interest rate. The price development rate projected until 2034 is assumed to continue unchanged through 2040.

<sup>29</sup> LiquidGas UK / SHV Energy (2022): Project KatJa! – On-Purpose BioLPG production from Ethanol, available [here](#). Futuria Fuels (2024): Ethanol to LPG: The Journey to a pilot plant and some of the challenges.

<sup>30</sup> This entails capital costs in 2025 of 20 million EUR(2025) for an annual output of 20k tonnes of renewable LPG. We assume capital cost decreases of 30% as learning curve effects until 2040 when scaling to commercial level.

<sup>31</sup> International Energy Agency (2025): World Energy Outlook 2025. Available [here](#).

## 5.2.3 bioDME

| <b>bioDME – Wholesale prices</b>           |  | <b>unit</b>                   | <b>2025</b>  | <b>2030</b>  | <b>2040</b>  |
|--|--|-------------------------------|--------------|--------------|--------------|
| Production cost                            |  | EUR(2025)/tonne(DME)          | 1,407        | 1,371        | 1,295        |
| of which annualis. capital costs           |  | EUR(2025)/tonne(DME)          | 3            | 3            | 3            |
| of which operating costs (incl. feedstock) |  | EUR(2025)/tonne(DME)          | 1,404        | 1,368        | 1,292        |
| Assumed margin*                            |  | EUR(2025)/tonne(DME)          | 87           | 76           | 64           |
| <b>Total wholesale price</b>               |  | <b>EUR(2025)/tonne(DME)</b>   | <b>1,494</b> | <b>1,447</b> | <b>1,359</b> |
| <b>Total wholesale price</b>               |  | <b>EUR(2025)/tonne(LPGeq)</b> | <b>2,351</b> | <b>2,278</b> | <b>2,139</b> |
| <b>Household prices</b>                    |  | <b>unit</b>                   | <b>2025</b>  | <b>2030</b>  | <b>2040</b>  |
| DE   |  | EUR(2025)/tonne(LPGeq)        | 3,598        | 3,511        | 3,346        |
|  |  | EUR(2025)/kWh                 | 0.28         | 0.27         | 0.26         |
| PL   |  | EUR(2025)/tonne(LPGeq)        | 3,473        | 3,383        | 3,212        |
|  |  | EUR(2025)/kWh                 | 0.27         | 0.26         | 0.25         |
| IT   |  | EUR(2025)/tonne(LPGeq)        | 3,739        | 3,649        | 3,480        |
|  |  | EUR(2025)/kWh                 | 0.29         | 0.28         | 0.27         |
| <b>Industry prices</b>                     |  | <b>unit</b>                   | <b>2025</b>  | <b>2030</b>  | <b>2040</b>  |
| DE   |  | EUR(2025)/tonne(LPGeq)        | 2,840        | 2,767        | 2,628        |
|  |  | EUR(2025)/kWh                 | 0.22         | 0.21         | 0.20         |
| PL   |  | EUR(2025)/tonne(LPGeq)        | 2,729        | 2,656        | 2,517        |
|  |  | EUR(2025)/kWh                 | 0.21         | 0.21         | 0.20         |
| IT   |  | EUR(2025)/tonne(LPGeq)        | 2,907        | 2,834        | 2,695        |
|  |  | EUR(2025)/kWh                 | 0.23         | 0.22         | 0.21         |

\* Margins are held constant in LPGeq, but are expressed in tonnes of DME here. Therefore, the value differs from those for the bioLPG pathways.

For bioDME, our wholesale price estimates rely on current biomethanol wholesale prices<sup>32</sup>, forecasted with cost developments from IRENA (2021)<sup>33</sup>. These are complemented with process information, such as yield from Fortin (2020)<sup>34</sup>. Operating costs decrease slightly due to modest reductions in energy costs (proxied by electricity price development Net Zero scenario via WEO 2025<sup>35</sup>, relevant operating cost share via Fortin (2020)<sup>36</sup>). The wholesale margin, in absolute terms, is assumed to be equal to that of bioLPG (HVO/HEFA) and to follow the same rate of reduction over time (please note that margins are assumed equal in tonne-LPGeq). The wholesale price premium of bioDME (in LPG-tonne-equivalent) relative to conventional LPG is added to the respective national LPG supply price (both at household and at industry level). Relevant additional price components, including energy taxes and applicable VAT, which are detailed in Chapter 5.1, are then applied.

## 5.3 Electricity prices

### 5.3.1 Electricity prices

| Electricity costs (Household prices) |        | 2025 | 2030 | 2040 |
|--------------------------------------|--------|------|------|------|
| DE                                   | ct/kWh | 0.39 | 0.38 | 0.36 |
| PL                                   | ct/kWh | 0.26 | 0.25 | 0.23 |
| IT                                   | ct/kWh | 0.33 | 0.32 | 0.30 |

<sup>32</sup> Validated against Argus Biomethanol fob Amsterdam-Rotterdam-Antwerp (ARA) [snapshot](#) and expert interviews.

<sup>33</sup> IRENA (2021): Innovation Outlook Renewable Methanol, available [here](#).

<sup>34</sup> Fortin, Cyril, et al. (2020): Dimethyl ether, A review of production processes and a modeling of the indirect route. Liege Univ: 1-20. Available [here](#). This includes capital costs of 3.78 million USD(2020) for an annual plant output for 116k tonnes of DME.

<sup>35</sup> International Energy Agency (2025): World Energy Outlook 2025. Available [here](#).

<sup>36</sup> Fortin, Cyril, et al. (2020): Dimethyl ether, A review of production processes and a modeling of the indirect route. Liege Univ: 1-20. Available [here](#).

Current prices are based on BDEW (2026)<sup>37</sup> and Eurostat (2026)<sup>38</sup>. German household prices are forecasted by combining electricity base prices based on Ariadne (2025)<sup>39</sup>, and separate forecasts of network charges by Consentec/Frontier Economics (2025)<sup>40</sup>. The resulting price development as of 2025 is mirrored for the Polish and Italian electricity prices. This simplifying assumption is validated against average electricity cost projections from Hasterok (2021)<sup>41</sup>, Elektrosiec (2025)<sup>42</sup>, and Peppoloni (2025)<sup>43</sup>.

### 5.3.2 Industry prices

| Electricity costs (Industry prices) | unit          | 2025 | 2030 | 2040 |
|-------------------------------------|---------------|------|------|------|
| DE                                  | EUR(2025)/kWh | 0.19 | 0.20 | 0.21 |
| PL                                  | EUR(2025)/kWh | 0.20 | 0.21 | 0.22 |
| IT                                  | EUR(2025)/kWh | 0.17 | 0.18 | 0.19 |

<sup>37</sup> BDEW (2026): Strompreisanalyse Januar 2026, available [here](#).

<sup>38</sup> Eurostat (2026): Electricity prices components for household consumers - annual data (from 2007 onwards) [nrg\_pc\_204\_c\_\_custom\_19780574].

<sup>39</sup> Gunnar Luderer (Hrsg.), Frederike Bartels (Hrsg.), Tom Brown (Hrsg.), Clara Aulich, Falk Benke, Tobias Fleiter, Fabio Frank, Helen Ganal, Julian Geis, Norman Gerhardt, Till Gnann, Alyssa Gunnemann, Robin Hasse, Andrea Herbst, Sebastian Herkel, Johanna Hoppe, Christoph Kost, Michael Krail, Michael Lindner, Marius Neuwirth, Hannah Nolte, Robert Pietzcker, Patrick Plötz, Matthias Rehfeldt, Felix Schreyer, Toni Seibold, Charlotte Senkpiel, Dominika Sörgel, Daniel Speth, Bjarne Steffen, Philipp C. Verpoort (2025): Die Energiewende kosteneffizient gestalten: Szenarien zur Klimaneutralität 2045. Kopernikus-Projekt Ariadne, Potsdam. <https://doi.org/10.48485/pik.2025.003>. Available [here](#).

<sup>40</sup> Consentenc and Frontier Economics for BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. (2025): Prognose und Analyse der Netzentgeltentwicklung. Available [here](#).

<sup>41</sup> Damian Adam Hasterok (2021): Poland's 2040 Energy Transition.

<sup>42</sup> Elektrosiec (2025): Prognoza cen energii elektrycznej do 2030: Kompleksowa analiza i perspektywy (available [here](#), accessed 22 January 2026).

<sup>43</sup> Giulia Peppoloni (2025): Long-term electricity price forecasting: merit order effect for 2030 in Italy.

As for household prices, current prices for non-household consumers from Eurostat (2026)<sup>44</sup>, excluding VAT and other recoverable taxes and levies. Forecast for Germany are based on industry electricity base price from Ariadne (2025)<sup>45</sup> and separate forecasts of network charges by Consentec/Frontier Economics (2025)<sup>46</sup>. For Poland and Italy, we apply the same price development as in Germany as of 2025 as a simplifying assumption which is validated against average electricity cost projections from Hasterok (2021)<sup>47</sup>, Elektrosiec (2025)<sup>48</sup>, and Peppoloni (2025)<sup>49</sup>.

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<sup>44</sup> Eurostat (2026): Electricity prices components for household consumers - annual data (from 2007 onwards) [nrg\_pc\_204\_c\_\_custom\_19780574].

<sup>45</sup> Gunnar Luderer (Hrsg.), Frederike Bartels (Hrsg.), Tom Brown (Hrsg.), Clara Aulich, Falk Benke, Tobias Fleiter, Fabio Frank, Helen Ganal, Julian Geis, Norman Gerhardt, Till Gnann, Alyssa Gunnemann, Robin Hasse, Andrea Herbst, Sebastian Herkel, Johanna Hoppe, Christoph Kost, Michael Krail, Michael Lindner, Marius Neuwirth, Hannah Nolte, Robert Pietzcker, Patrick Plötz, Matthias Rehfeldt, Felix Schreyer, Toni Seibold, Charlotte Senkpiel, Dominika Sörgel, Daniel Speth, Bjarne Steffen, Philipp C. Verpoort (2025): Die Energiewende kosteneffizient gestalten: Szenarien zur Klimaneutralität 2045. Kopernikus-Projekt Ariadne, Potsdam. <https://doi.org/10.48485/pik.2025.003>. Available [here](#).

<sup>46</sup> Consentenc and Frontier Economics for BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. (2025): Prognose und Analyse der Netzentgeltentwicklung. Available [here](#).

<sup>47</sup> Damian Adam Hasterok (2021): Poland's 2040 Energy Transition.

<sup>48</sup> Elektrosiec (2025): Prognoza cen energii elektrycznej do 2030: Kompleksowa analiza i perspektywy (available [here](#), accessed 22 January 2026).

<sup>49</sup> Giulia Peppoloni (2025): Long-term electricity price forecasting: merit order effect for 2030 in Italy.

## 5.4 Other costs and prices

| Capital costs + installation | unit             | 2025  | 2030  | 2040  | Source   |
|------------------------------|------------------|-------|-------|-------|--|
| ASHP_radiator                | EUR(2025)/kW(th) | 4,412 | 4,191 | 3,750 | dena (2025) <sup>50</sup> , Markup on lower-temp HP based on Palmer and Terry (2021) <sup>51</sup> |
| ASHP_floor                   | EUR(2025)/kW(th) | 3,960 | 3,762 | 3,366 | dena (2025) <sup>52</sup>  |
| LPG / rLG boiler             | Flat             | 2,500 | 2,500 | 2,500 | Liquid Gas UK (2020) <sup>53</sup>   |

To ensure comparability, we assume a uniform lifetime of 20 years for all heating technologies. Capital costs are annualised using a 5% discount rate.

| O&M costs        | unit           | 2025 | 2030 | 2040 | Source   |
|------------------|----------------|------|------|------|--|
| ASHP_radiator    | EUR(2025) p.a. | 420  | 420  | 420  | dena (2025) <sup>54</sup>  |
| ASHP_floor       | EUR(2025) p.a. | 420  | 420  | 420  | dena (2025) <sup>55</sup>  |
| LPG / rLG boiler | EUR(2025) p.a. | 255  | 255  | 255  | dena (2025) <sup>56</sup> plus LPG tank rental based on Liquid Gas UK (2020) <sup>57</sup> |

<sup>50</sup> Deutsche Energie-Agentur GmbH (Hrsg.) (dena, 2025) KWW-Technikkatalog Wärmeplanung.. Available [here](#).

<sup>51</sup> Palmer, Jason, and Nicola Terry. *Cost-optimal domestic electrification (CODE)*. Department for Business, Energy & Industrial Strategy, 2021. Available [here](#).

<sup>52</sup> Deutsche Energie-Agentur GmbH (Hrsg.) (dena, 2025) KWW-Technikkatalog Wärmeplanung.. Available [here](#).

<sup>53</sup> Liquid Gas UK (2020): The Role of LPG and bioLPG in Large, Rural Off-Grid Homes. Available [here](#).

<sup>54</sup> Deutsche Energie-Agentur GmbH (Hrsg.) (dena, 2025) KWW-Technikkatalog Wärmeplanung.. Available [here](#).

<sup>55</sup> Deutsche Energie-Agentur GmbH (Hrsg.) (dena, 2025) KWW-Technikkatalog Wärmeplanung.. Available [here](#).

<sup>56</sup> Deutsche Energie-Agentur GmbH (Hrsg.) (dena, 2025) KWW-Technikkatalog Wärmeplanung.. Available [here](#).

<sup>57</sup> Liquid Gas UK (2020): The Role of LPG and bioLPG in Large, Rural Off-Grid Homes. Available [here](#).

## 5.5 Emission intensities

| Emission intensity of electricity generation | unit       | 2025 | 2030 | 2040 | Source  |
|--|------------|------|------|------|---|
| DE   | kg CO2/kWh | 0.33 | 0.10 | 0.03 | Ember (2026) <sup>58</sup> ,<br>Ariadne (2025) <sup>59</sup>  |
| PL   | kg CO2/kWh | 0.59 | 0.29 | 0.05 | Ember (2026) <sup>60</sup> ,<br>CAKE (2022) <sup>61</sup> ,<br>BloombergNEF (2023) <sup>62</sup>          |
| IT   | kg CO2/kWh | 0.29 | 0.15 | 0.03 | Ember (2026) <sup>63</sup> ,<br>ECCO/E3G (2024) <sup>64</sup> ,<br>Climate Analytics (2026) <sup>65</sup> |

<sup>58</sup> Ember Electricity Data Explorer (2026), available [here](#).

<sup>59</sup> Gunnar Luderer (Hrsg.), Frederike Bartels (Hrsg.), Tom Brown (Hrsg.), Clara Aulich, Falk Benke, Tobias Fleiter, Fabio Frank, Helen Ganal, Julian Geis, Norman Gerhardt, Till Gnann, Alyssa Gunnemann, Robin Hasse, Andrea Herbst, Sebastian Herkel, Johanna Hoppe, Christoph Kost, Michael Krail, Michael Lindner, Marius Neuwirth, Hannah Nolte, Robert Pietzcker, Patrick Plötz, Matthias Rehfeldt, Felix Schreyer, Toni Seibold, Charlotte Senkpiel, Dominika Sörgel, Daniel Speth, Bjarne Steffen, Philipp C. Verpoort (2025): Die Energiewende kosteneffizient gestalten: Szenarien zur Klimaneutralität 2045. Kopernikus-Projekt Ariadne, Potsdam. <https://doi.org/10.48485/pik.2025.003>. Available [here](#).

<sup>60</sup> Ember Electricity Data Explorer (2026), available [here](#).

<sup>61</sup> Centre for Climate and Energy Analyses (2022): Poland Net-Zero 2050 Transformation Of The Polish And Eu Energy Sector Until 2050. Available [here](#).

<sup>62</sup> BloombergNEF / Felicia Aminoff (2023): Poland Power Transition Outlook 2023. Three scenarios until 2040.

<sup>63</sup> Ember Electricity Data Explorer (2026), available [here](#).

<sup>64</sup> ECCO/E3G (2024): G7 Power Systems Scorecard. Country profile Italy. Available [here](#).

<sup>65</sup> Climate Analytics (2026): 1.5° National Pathway Explorer. Available [here](#).

Moreover, we consider lump-sum LCA mark-ups on electricity generation for (planned) RES capacities (wind and PV), approximated with FVV (2022)<sup>66</sup> and TYNDP 2024<sup>67</sup>. These mark-ups range from 0.01 to 0.03 kg CO<sub>2</sub>/kWh. This ensures comparability with the LCA emission factors for rLG.

For the emission intensity of LPG, we consider a flat 0.29 kg CO<sub>2</sub>/kWh which is also considering an LCA mark-up based on Unnasch and Goyal (2017)<sup>68</sup>. For rLG, we consider a flat 0.09 kg CO<sub>2</sub>/kWh (which is equivalent to the reference value of 24 g CO<sub>2</sub>/MJ and consistent with compliance under current EU Renewable Energy Directive greenhouse gas saving thresholds).

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<sup>66</sup> FVV eV (2022): Future Fuels: FVV Fuel Study IVb. Annex – Technical subreport (ifeu). Emission factors for electricity generation (9.4.3).

<sup>67</sup> TYNDP 2024: Supply Inputs for TYNDP 2024 Scenarios After Public Consultation.

<sup>68</sup> Unnasch, Stefan, and Love Goyal. "Life cycle analysis of LPG transportation fuels under the Californian LCFS." *Life Cycle Associates Report LCA 8103* (2017): 2017. Available [here](#).

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