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# Comparing energy technologies across alternative regulatory scenarios: profitability, promotion schemes and the potential for a cost-efficient decarbonization of the German residential sector

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## ABSTRACT

We assess alternative energy technologies for German single-family houses (i.e., hybrid gas heating with solar thermal energy, electric heat pumps, PV and BES systems) in terms of profitability and $CO_2$ emissions. Under the status-quo regulatory framework, the energy transition in the heating sector is fostered through grants for replacing old heating systems, whereas PV generation is fostered by feed-in tariffs and indirect subsidies for self-consumption. We consider alternative regulatory scenarios with a more market-oriented approach, finding that a $CO_2$-oriented reform of energy surcharges and taxes, as well as a reform of network charges, can support a more cost-efficient energy transition in the residential sector.

**Keywords:** heat pump, solar thermal energy, PV, regulatory framework, heating sector, prosumer.

## NOMENCLATURE

| *Abbreviations* | |
|---|---|
| GCB | gas condensing boiler |
| OGB | old gas boiler |
| STE | solar thermal energy |
| HP | air-to-water heat pump |
| COP | coefficient of performance |
| HES | house energy systems |
| BES | battery energy storage |
| FiT | feed-in tariff |
| DCF | discounted cash flow |
| DHW | domestic hot water |
| VAT | value-added tax |
| IPH | Investment planning horizon |

## 1. INTRODUCTION

The heating sector represents a major part of Germany's decarbonization challenge, accounting for approximately half of all German energy consumption and currently relying predominantly on fossil fuels [1], especially gas-based heating systems [2]. As of 2020, approximately 1.1 million heat pumps were in place compared to 13.9 million gas heating systems [2]. The new German government has strengthened the ambitions for decarbonization, setting the target for heat pumps at 6 million by 2030, and committing to the goal that, from 2025, renewable energy will meet 65% of the energy needs of new heating systems [3].

The German Energy Transition has traditionally focused on the electricity sector, with centralized promotional schemes that reward the feed-in of renewable electricity into the electricity grid. In contrast, the heating sector is much more fragmented, making the coordination and organization of the transition to low-carbon technologies more difficult [4]. For example, there are severe difficulties with implementation capacities in the heating trade sector and also uncertainty arising from the shift in government strategy from the promotion of hybrid gas heating systems to a much greater focus on heat pumps [5]. Low-carbon heating systems have received subsidies in Germany since 1999, under the market incentive program, involving direct cash subsidies for technologies [6]. Currently, subsidies foster the replacement of old boilers with entirely low-carbon heat technologies, such as heat pumps and biomass systems, as well as hybrid systems, such as gas condensing boilers (GCB) with solar thermal energy (STE) systems. Subsidies are designed to cover a percentage of the investment costs associated with a new heating technology ranging from 30% of investment costs for hybrid GCB + STE systems to 35% for heat pumps and other renewable heating systems. Subsidy rates are increased by 10 percentage points when technologies replace old oil boilers, whereas additional heating-related investments (e.g., aeration systems) receive a grant covering 20% of the costs [7]. While there is recognition that a mix of technologies will be required, it is certain that an increasing share of electricity-based technologies will be central to the decarbonization of heat and the regulatory framework should reform levies on renewable electricity [1].

This paper considers how alternative regulatory scenarios affect price signals for the adoption and optimal operation of alternative house energy systems (HESs), consisting of PV and BES systems, an hybrid gas heating with solar thermal energy or an electric air-to-water heat pump (HP). We are interested in (i) the extent to which technology adoption and operation strategy is incentivized and (ii) how the households' financially optimal decisions perform in terms of $CO_2$ emissions savings.

In this study, we consider a "Business as usual" (*BAU_sub*) scenario, based on retail energy tariffs (incl. PV FiTs) available in the first half of 2021[1] to household consumers and the above-mentioned subsidies for new heating systems. We compare this *BAU_sub* scenario to an alternative regulatory scenario (*CC&Ene_ref*) in which a more market-oriented approach consisting of two policy reforms is implemented. Firstly, a fundamental reform of electricity network charges, in which infrastructure costs are recovered through capacity charges rather than volumetric charges, while coincident demand and feed-in charges aim to incentivize a more efficient use of the grid. Secondly, an energy reform by which all energy taxes and surcharges are abolished and replaced with a uniform $CO_2$ pricing mechanism, leading to increases in gas retail prices and average wholesale electricity prices. At the same time, dynamic retail prices are adopted, meaning that the high variance in wholesale electricity prices incentivizes load shifting to periods of low-carbon electricity generation. Similarly, for electricity exported to the grid, the fixed feed-in tariff is replaced by a time-varying export rate. Overall, such policy reforms lead to lower volumetric electricity retail prices, which tend to improve the profitability of electrical heating, and to a grid- and low-carbon-oriented operation of BES and HPs.

*Table 1 - Yearly energy demand of the simulated household (kWh)*

| | |
|---|---|
| ***Electricity Demand*** | 4,903 |
| ***DHW*** | 2,659 |
| ***Space Heating*** | 12,895 |

## 2. MATERIALS AND METHODS

### *2.1 Data & Assumptions*

The methodology of this study is based on a set of data and assumptions, which are reported in detail in [8]. Here, we summarize the most important input data used in this paper. We use synthetic load profiles of electricity, domestic hot water (DHW) and space heating demand for a 4-person household based in Essen, Germany, living in $150m^2$ single-family house equipped with an old gas boiler (OGB)[2] (data on energy demand is given in Table 1). With regard to the supply side, we use location-specific PV generation profiles, estimated hourly intensity of grid electricity and real-time network conditions, as well as hourly wholesale electricity prices, which all refer to the year 2019[3]. By means of data on carbon allowances prices, we estimate hourly wholesale electricity prices of the *CC & Ene_ref* scenario, in which we assume a national level $CO_2$ price of 125 €/t, which is deemed sufficient for the implementation of a revenue-neutral reform of energy taxes and surcharges [9]. The integration of high $CO_2$ prices into wholesale electricity prices feeds through into retail prices, yet this effect is far outweighed by the impact of the removal of surcharges and electricity taxes, with retail electricity prices, in fact, falling. Injection into the grid is remunerated with the same dynamic prices as withdrawals (except for VAT and concession fee). Moreover, the replacement of volumetric network charges with capacity-based charges results in a further reduction in volumetric retail electricity prices under this regulatory scenario. For the two scenarios, the structure of electricity and gas tariffs is given in Table 2.

In this study, the household is seeking to replace an old gas boiler with (i) a hybrid GCB+ STE system or (ii) an HP. Moreover, the household can invest in an optional PV system and in BES. The investment, operating costs and grant[4] for PV, batteries and heating systems are given in Table 3 and Table 4. With respect to the heating systems, based on the simulation of [8] and on [10], we assume that the GCB and OGB systems have a final efficiency (i.e., the ratio between supplied heating energy and input energy) of 97.3%, and of 80.4%, respectively. The HP has a variable COP and additional losses associated with space heating storage, which is why its final efficiency depends on its operation (see [8] for details). All HES' components are assumed to have a

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[1] Energy prices soared to unprecedented levels in the second half of 2021. If such price level becomes permanent, this will affect significantly the financial assessment of HESs. In this paper, we assume households face the market conditions that existed at the start of 2021, with respect to energy costs, technology costs, system costs and inflation.

[2] Gas-based heating is by far the most common option among the existing heating generators [2]

[3] We consider the first half of 2021 and 2019 two similar periods in terms of the general energy market condition. However, we try to harmonize retail electricity tariffs between the two scenarios, as these rely on data referring to these two different years (see [8] for details).

[4] Grant levels vary for the different cost components of the new heating system, as heating-related costs are covered with a 20%-grant. (cf. Introduction)

lifetime of 20 years (except for the BES, which can be replaced during the analysis period).

## *2.2 Modeling Approach*

The modeling approach consists of two modules, namely (i) an operation module and (ii) an investment module. The operation module optimizes the energy dispatch of a given HES in the first year of operation. It calculates the optimized dispatch of PV electricity and optimal operation of the heat pump and battery system[5].

The investment module considers the optimized energy dispatch, resulting from the operation module, and extends it over an investment planning horizon (IPH) of 20 years. It considers PV and battery degradation, as well as increase in prices and the decline in the emission intensity of grid electricity. This results in the assessment of the financial performance and impact on $CO_2$ emissions of each HES under the two regulatory scenarios.

*Table 4 - Cost of PV and BES systems (Including VAT, based on [8])*

| | **PV** | | | |
|---|---|---|---|---|
| ***Nominal Power (kW)*** | 5 | 7.5 | 9.9 | 15 |
| ***Investment costs (€)*** | 7,559 | 10,308 | 12,495 | 17,805 |
| ***Operating costs (€/y)*** | 150 | 175 | 200 | 250 |
| | **BES** | | | |
| ***Nominal capacity (kWh)*** | 3.3 | 6.7 | 10 | 13.3 |
| ***Maximum power (kW)*** | 3 | 4 | 5 | 5 |
| ***Investment costs (€)*** | 6,614 | 7,879 | 9,299 | 9,547 |
| ***Operating costs (€/y)*** | 0 | 0 | 0 | 0 |
| ***Replacement costs (€)*** | 900 | 1,800 | 2,700 | 3,600 |

*Table 2 - Structure of electricity and gas tariffs, dynamic rates are reported as a range of values. Negative values indicate revenues. (Including VAT, based on [8])*

| ***Scenario*** | **Charge type** | **Std. power** | **HP power** | **Feed-in (<10 kW)** | **Feed-in (>10 kW)** | **Gas** |
|---|---|---|---|---|---|---|
| ***BAU*** | Flat volumetric (ct/kWh) | 26.07 | 19.41 | -8.16 | -7.93 | 4.63 |
| | Fixed (€/year) | 118.52 | 66.46 | - | - | 136.69 |
| ***CC&Ene_ref*** | Flat volumetric (ct/kWh) | 2.84 | | - | - | 6.16 |
| | Dynamic volumetric (ct/kWh) | [-7.62 ,21.53] | | -[-7.62,18.08] | | - |
| | On-peak capacity (€/KW/month) | 5 | | 5 | | - |
| | Off-peak demand (€/KW/month) | 2.5 (min 2.6 kW) | | - | - | - |
| | Fixed (€/year) | 40.34 | 66.46 | - | - | 136.69 |

*Table 3 – Costs of heating systems (Including VAT, based on [10])*

| | **OGB** | **GCB + STE** | **HP** |
|---|---|---|---|
| ***Investment costs (€)*** | 0 | 19,100 | 23,820 |
| ***Operating costs (€/y)*** | 573 | 525 | 440 |
| ***Grant (€)*** | 0 | 5,460 | 7,447 |

## 3. RESULTS

In this section, we report:

- the financial performance, in terms of the DCF of net costs (i.e., the difference between energy and system costs and feed-in revenues) over the IPH
- the impact on $CO_2$ emissions[6], in terms of net emissions (i.e., the difference between emissions caused by household energy demand and those displaced through PV feed-in), over the same period

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[5] The hybrid heating system, in contrast, barely needs any optimization, as it operates independent of dynamic electricity prices, capacity-charges and PV generation, whereas we assume a fixed self-sufficiency rate of 22% by means of STE, based on [11].

[6] We consider emissions over the IPH rather than over the entire lifecycle of technologies.

In the case of *BAU_sub*, the status-quo scenario with subsidies for heating technologies, the hybrid GCB + STE system shows a significantly better financial performance than the HP when there is no PV capacity and when PV capacity is below 7.5 $kW_p$. For instance, without PV, it shows a DCF that is approximately 5% lower than that of the HP (cf. Table 5). From a PV capacity of 7.5 $kW_p$, the heat pump performs better financially, because of higher self-consumption savings. This self-consumption saving reflects the high volumetric electricity rates in this scenario. BES adversely affects financial performance, but there can still be non-financial motivations to adopt batteries (e.g. for the purposes of greater independence from the grid), which is why it is important to understand the impact of their operation.

In the *CC&Ene_ref* scenario, investment grants are withdrawn and it is clear from Table 5 that the heat pump outperforms the hybrid system. Under this scenario, it is less worthwhile to install PV systems, especially small ones, and batteries have a more significant negative effect on profitability. This is because retail electricity prices (and, hence, the role of self-consumption savings) are lower[7] under the *CC&Ene_ref* scenario thanks to the removal of volumetric network charges, surcharges and taxes. The uniform $CO_2$ price (levied also on gas) coupled with the reduced retail electricity prices appears to shift the financial attractiveness clearly in favor of the HP. It is interesting to note that, in the case when no PV is installed, despite the removal of grants for renewable heating technologies existing in the *BAU_sub* scenario, the financial performance of the heat pump is significantly superior under this alternative scenario. This implies that the effect of the reduced retail electricity prices outweighs the effect of the withdrawal of subsidies.

Table 6 highlights that, for both scenarios, the HP is preferable in terms of carbon emission reductions and that, from a capacity of 9.9 $kW_p$ PV capacity, they lead to negative emissions, meaning that displaced emissions surpass demand-related emissions. Moreover, Table 6 shows that the avoided emissions are significantly greater in the *CC&Ene_ref* scenario and this reflects the incentives to operate the household energy system in a more climate-friendly way thanks to dynamic prices. This is especially true in the case of large BES, as this offers more capacity for load shifting to low-carbon, low-cost periods, and feed-in shifting to high-carbon, high-cost ones.

Grants in the *BAU_sub* scenario, which lead to similar, and, sometimes, better financial performance for the hybrid system compared to the heat pump, do not reflect the superior performance of heat pumps in terms of emissions. In this respect, we consider the cost in terms of DCF for each ton of avoided $CO_2$ emissions, by comparing the investment in a new HES to the continued operation of the OGB[8]. Under the *BAU_sub* scenario, the stand-alone heat pump shows a cost per avoided ton of $CO_2$ 53% lower than the stand-alone hybrid GCB + STE system (i.e., 543€/$tCO_2$ and 1,149 €/$tCO_2$, respectively). Such a gap reflects the far higher cost-efficiency in reducing $CO_2$ emission of the HP. Under the *CC&Ene_ref* scenario, this difference increases. The cost of avoided $CO_2$ associated with the heat pump is 62% lower than the in the case of the GCB + STE (i.e., 409€/$tCO_2$ and 1,081€/$tCO_2$, respectively). This increasing divergence can be attributed to the higher price of gas under the *CC&Ene_ref* scenario and the lower retail price of electricity. Moreover, in the *BAU_sub* scenario, an additional cost per avoided ton of $CO_2$ is covered by the grant, amounting to €196 and €116 per ton of $CO_2$, for the hybrid GCB and the HP, respectively.

## 4. DISCUSSION AND CONCLUSIONS

The design of the German *Wärmewende* (i.e., energy transition in the heating sector) appears to be currently inefficient in meeting the desired decarbonization goals. Given the available subsidies, hybrid GCB + STE systems enjoy substantial financial support despite the fact that heat pumps offer far superior performance on emissions. Heat pumps are penalized by expensive electricity prices, which are composed substantially of regulatory components. This has contributed to the hitherto slow uptake of heat pumps in Germany – for example, in 2021, only ca. 154,200 heat pumps were installed in Germany, as opposed to 573,200 gas condensing boilers [12], which is currently inconsistent with the goals outlined by the German government.

Our research suggests that a more effective policy would be to shift from subsidizing technologies to penalizing $CO_2$ – as represented in the *CC&Ene_ref* scenario. Heat pumps retain their financial attractiveness despite the removal of subsidies in the *CC&Ene_ref* scenario, thanks to the effect of reforming the regulated components[9] of electricity prices, i.e., taxes, surcharges and network fees. Furthermore, dynamic prices lead to a

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[7] In the first year of the IPH, average standard-electricity volumetric rates fall from approx. 26.1 ct/kWh to approx. 12 ct/kWh. Deferrable HP load is optimized to further reduce the average withdrawal price, which is why average HP power rates fall from 19.4 ct/kWh to 10.7 ct/kWh (in the case of an HES without PV and BES).

[8] We assume that the OGB can be operated over the IPH without any additional investment.

[9] As a matter of fact, the EEG surcharge, the most important levy burdening retail prices will be abolished in the upcoming months. However, such a reduction in regulated components will be more than offset by the surge in wholesale energy prices.

more favorable operation of the heat pumps, which enhances the reduction of $CO_2$ emissions.

As a result, the cost of $CO_2$ emissions reduction is, generally, much lower in the *CC&Ene_ref* scenario, for heat pumps. This is advantageous both to households and also to the government that no longer has expenditure associated with the subsidy. The cost of $CO_2$ emissions reduction through hybrid GCB + STE systems is far higher for both scenarios, leading to a less economically efficient decarbonization of the heating sector. Given the large scale of the *Wärmewende* and the need to accelerate the deployment of renewable heating technologies, it is vital that this is done in a way that is economically optimal and focusing on $CO_2$ would appear to be a better option.

Whilst this study is indicative of the problems with the status-quo regulatory framework[10], it only considers one type of building, location and household, whereas the residential sector is very heterogeneous. Moreover, it would be interesting to consider a wider variety of technologies, including, e.g., pellet boilers and fuel cells, as well as alternative levels of building refurbishment. Overall, there is a need for further research in this area, especially considering that the goal of the decarbonization of the heating sector is increasingly related to urgent geopolitical matters.

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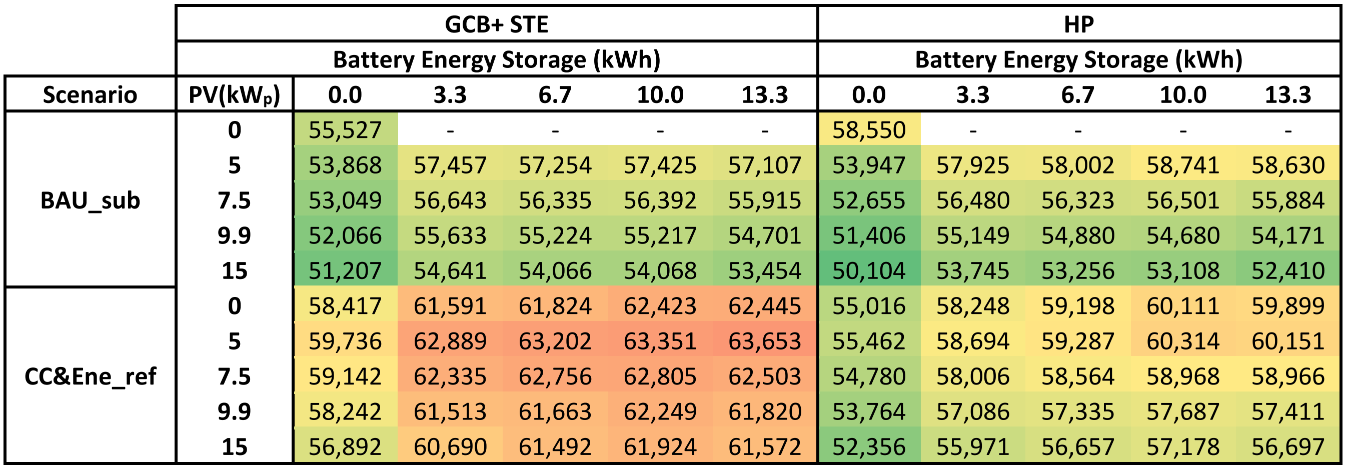
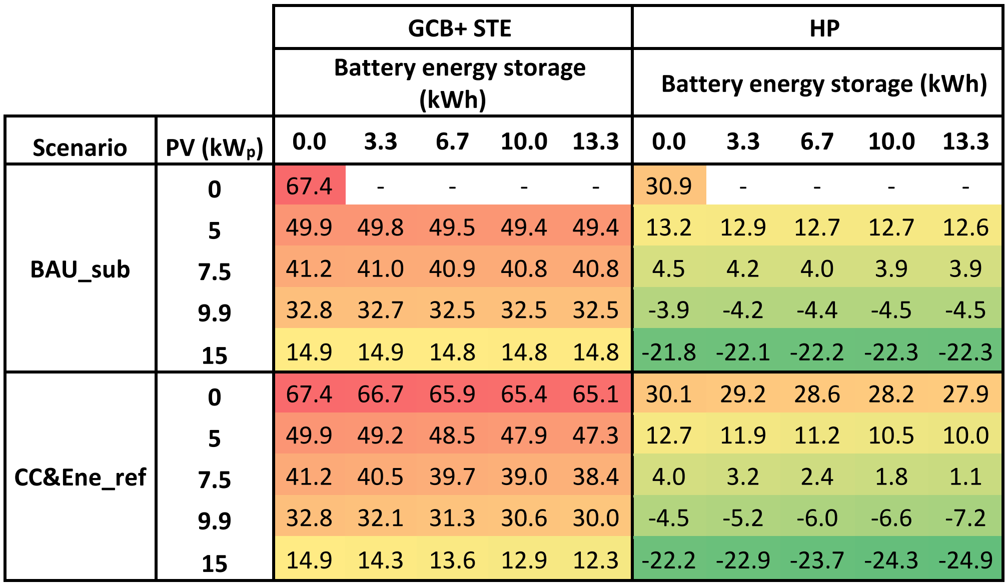
[10] As noted before, the regulatory framework in place until 2021 is already rapidly changing under the pressure of unprecedented market conditions.

*Table 5 – Results: DCF(€)*



| | | GCB+ STE | | | | | HP | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Battery Energy Storage (kWh) | | | | | Battery Energy Storage (kWh) | | | | |
| **Scenario** | **PV(kW$_p$)** | **0.0** | **3.3** | **6.7** | **10.0** | **13.3** | **0.0** | **3.3** | **6.7** | **10.0** | **13.3** |
| **BAU_sub** | **0** | 55,527 | - | - | - | - | 58,550 | - | - | - | - |
| | **5** | 53,868 | 57,457 | 57,254 | 57,425 | 57,107 | 53,947 | 57,925 | 58,002 | 58,741 | 58,630 |
| | **7.5** | 53,049 | 56,643 | 56,335 | 56,392 | 55,915 | 52,655 | 56,480 | 56,323 | 56,501 | 55,884 |
| | **9.9** | 52,066 | 55,633 | 55,224 | 55,217 | 54,701 | 51,406 | 55,149 | 54,880 | 54,680 | 54,171 |
| | **15** | 51,207 | 54,641 | 54,066 | 54,068 | 53,454 | 50,104 | 53,745 | 53,256 | 53,108 | 52,410 |
| **CC&Ene_ref** | **0** | 58,417 | 61,591 | 61,824 | 62,423 | 62,445 | 55,016 | 58,248 | 59,198 | 60,111 | 59,899 |
| | **5** | 59,736 | 62,889 | 63,202 | 63,351 | 63,653 | 55,462 | 58,694 | 59,287 | 60,314 | 60,151 |
| | **7.5** | 59,142 | 62,335 | 62,756 | 62,805 | 62,503 | 54,780 | 58,006 | 58,564 | 58,968 | 58,966 |
| | **9.9** | 58,242 | 61,513 | 61,663 | 62,249 | 61,820 | 53,764 | 57,086 | 57,335 | 57,687 | 57,411 |
| | **15** | 56,892 | 60,690 | 61,492 | 61,924 | 61,572 | 52,356 | 55,971 | 56,657 | 57,178 | 56,697 |

*Table 6 – Results: Net CO$_2$ emissions (t) over the IPH*



| | | GCB+ STE | | | | | HP | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Battery energy storage (kWh) | | | | | Battery energy storage (kWh) | | | | |
| **Scenario** | **PV (kW$_p$)** | **0.0** | **3.3** | **6.7** | **10.0** | **13.3** | **0.0** | **3.3** | **6.7** | **10.0** | **13.3** |
| **BAU_sub** | **0** | 67.4 | - | - | - | - | 30.9 | - | - | - | - |
| | **5** | 49.9 | 49.8 | 49.5 | 49.4 | 49.4 | 13.2 | 12.9 | 12.7 | 12.7 | 12.6 |
| | **7.5** | 41.2 | 41.0 | 40.9 | 40.8 | 40.8 | 4.5 | 4.2 | 4.0 | 3.9 | 3.9 |
| | **9.9** | 32.8 | 32.7 | 32.5 | 32.5 | 32.5 | -3.9 | -4.2 | -4.4 | -4.5 | -4.5 |
| | **15** | 14.9 | 14.9 | 14.8 | 14.8 | 14.8 | -21.8 | -22.1 | -22.2 | -22.3 | -22.3 |
| **CC&Ene_ref** | **0** | 67.4 | 66.7 | 65.9 | 65.4 | 65.1 | 30.1 | 29.2 | 28.6 | 28.2 | 27.9 |
| | **5** | 49.9 | 49.2 | 48.5 | 47.9 | 47.3 | 12.7 | 11.9 | 11.2 | 10.5 | 10.0 |
| | **7.5** | 41.2 | 40.5 | 39.7 | 39.0 | 38.4 | 4.0 | 3.2 | 2.4 | 1.8 | 1.1 |
| | **9.9** | 32.8 | 32.1 | 31.3 | 30.6 | 30.0 | -4.5 | -5.2 | -6.0 | -6.6 | -7.2 |
| | **15** | 14.9 | 14.3 | 13.6 | 12.9 | 12.3 | -22.2 | -22.9 | -23.7 | -24.3 | -24.9 |

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