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Accounting for economic disparity in designing net-zero European energy systems

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Abstract

High-resolution energy system models, as powerful tools to represent energy systems in detail and assist energy transition planning, rarely account for economic disparity, unlike broader-scale tools such as integrated assessment models. In this study, by analysing net-zero European energy system designs through the lens of national gross domestic product (GDP) and household average income, we find that disparity-unaware high-resolution energy system models can produce results that are technically feasible but largely incompatible with economic realities. The investment in household heating technology may be disproportional to the income level of lower-income countries. Explicitly acknowledging economic disparity in such models reduces the danger of them proposing solutions which burden economically disadvantaged actors. Therefore, here, we explicitly include national GDP and household income disparity in a model for net-zero European energy system designs. We find that disparity-compatible systems are possible with a 1.1% total system cost increase compared to the least-cost ones. Unlike in disparity-unaware system designs, where energy infrastructure investments often reach over 20% of national GDP for some countries, we develop disparity-compatible designs which limit investments to below 5% in each country. Our results show that less affluent European countries may need substantial household-level financing to support their heating transition and to diversify their net-zero energy technology choices.

1. Introduction

European countries are at various levels of economic development but share common decarbonisation policy goals. This is also true among EU member states. For example, the median income of the Netherlands is roughly four times that of Romania [1], but both are committed to the EU decarbonisation goal of net-zero greenhouse gas emission by 2050 [2]. Therefore, the distribution of the burdens and benefits is one of the central concerns in the energy transition at the European level [3].

Modellers in the field of climate change mitigation have already acknowledged the differences in economic conditions and capabilities between countries and actors. On a national or international scale, there have been studies that discuss regional inequality [4–6], which has a justice implication [7]. There is a rich literature regarding the connection between regional economic inequality and social cost of carbon and climate damage [4, 5, 8], but less has been researched regarding the cost needed for renewable energy expansion and investment. Studies such as Taconet *et al* [9] connect differentiated economic capability to climate mitigation costs, but remain unspecific to the energy system and different possible system configurations. On a household level, previous researchers have investigated the intricacies between climate policies and household income inequalities, both on a sub-national [10] and on a national [11] scale. However, none of these studies above connects economic inequality and potentially different energy system configurations for a swift energy transition. On the other hand, studies that are able to account for details in energy system configurations, utilising energy system models, have not fully addressed economic inequality, despite existing proposals to link them [12, 13].

High-resolution energy system models are important tools to support planning for the capacity expansion needed to build a renewable energy system. They can capture the intermittency of renewable energies and balance demand and supply, ensuring the technical feasibility of the modelled energy system through high spatiotemporal resolutions. With the growing emphasis on renewable energy, this specific type of energy system model has gained research and policy attention in recent years [14]. They become an important type of evidence in energy transition policies, helping in impact assessment, target setting and exploring policy options for these targets [15, 16]. Yet, despite the technical strengths of such models on national scales and above, they remain lacking in addressing policy goals such as burden and benefit sharing [17]. The techno-economic feasibility of these models does not necessarily translate into real-world implementation viability. Most studies that claim equitable system designs have not accounted for the existing differences in economic conditions between regions and actors when generating system designs. They define burden as the relationship between energy supply and demand [18, 19], or the relationship between electricity production and the production potential [20]. That overlooks the differentiated economic capability of different regions, which is also highly relevant to the transition, especially in a type of model that centres on monetary costs. Only two energy system modelling studies account for economic disparity between regions [21, 22], but they include this disparity to assess system designs *after* the model has designed them, rather than being guiding or constraining principles in the modelling itself. Thus, existing models, which we call 'disparity-unaware', are unable to explore system designs that cater to economic disparity, which, if considered, could contribute to implementation viability. Recently, to explore the diversity of technical system designs, modelling to generate alternatives (MGAs) algorithms [23], which yield many near-optimal system designs, have been adopted by modellers [21, 22, 24, 25] and are framed as a method to make system designs that fulfil different policy goals and preferences [26]. Such approaches can serve as a departure point to build a 'disparity-aware' modelling approach that explicitly considers the viability of system designs through different social conditions and value lenses.

The distribution of added energy technology infrastructure within Europe comes with significant social relevance. A high investment volume that goes beyond the current economic capability of a region, industry, or segment of society, such as households, can be viewed both positively and negatively. On the one hand, external investment into an economically disadvantaged entity can reduce inequality [27], for example, leading to regional economic development or improving household living standards. On the other hand, without external support, it can imply additional economic burden [28, 29]. Leaving all actors as-is without any policy intervention might render an imbalanced and difficult transition. For modelling studies that ultimately inform policy making, it is therefore important to account for economic disparities within Europe: if decisions were to be made based on modelling studies that are disparity-unaware, economically disadvantaged groups may be unexpectedly overburdened.

In this paper, we attempt to link modelling to the policy ambition of a smooth energy transition by explicitly accounting for economic disparity in model-based designs of the future European energy system. Our work expands on the sector-coupled Euro-Calliope model and the SPORES MGA algorithm introduced in Pickering *et al* [24] and Lombardi *et al* [26], respectively. We first compare investment plans to European countries' national gross domestic product (GDP) and average household income to estimate what a disparity-unaware model formulation leads to in terms of investment distributions compared to each European country's economic capability. Then, we introduce additional model constraints to avoid a significant mismatch between energy investments and current economic capabilities. This allows us to quantitatively identify potential transition bottlenecks and the extent to which additional policy intervention may be needed to address them.

2. Methods

We propose two ways to assess distributive features of various energy system designs from the perspective of current economic disparity and add this perspective to an energy system model. The first section explains how the distributive features are calculated and assessed, and the second section describes in detail the two models we use, including how we generate alternative system designs with disparity-aware constraints.

2.1. Evaluation of distributive features in energy system designs

Our work concerns net-zero European energy system designs that outline how Europe can reach its decarbonisation goal. Each design describes a configuration of European energy infrastructure determined by a capacity expansion model. We assess these system designs from two perspectives: (1)

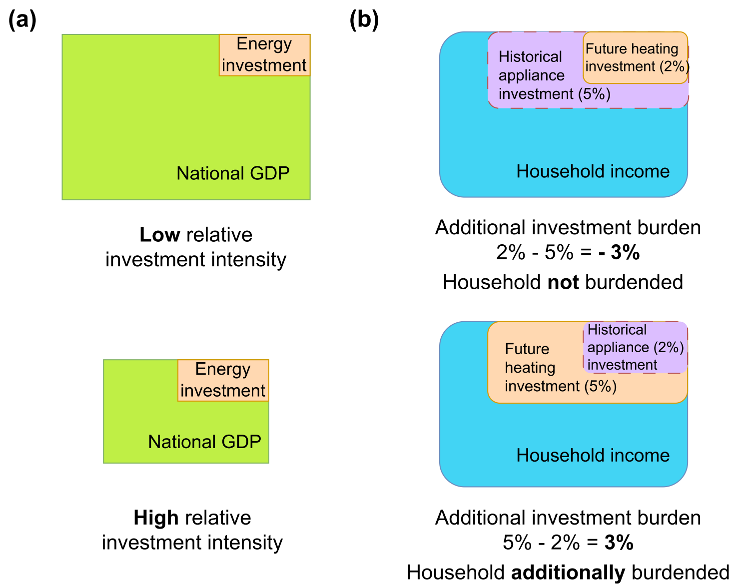

Figure 1. Explanation of the two main indices to describe the investment level of a country used in this study. (a) Explanation of relative investment intensity on non-household energy technology investments. (b) Explanation of the household's additional investment burden.

non-household energy infrastructure investment and (2) household heating technology investment. These perspectives are chosen because we would like to assess energy investments from both a public domain (what the transition investment generally means to a national economy) and a private domain (how much investments need to be realised by households). We choose to focus on heating here because heating has been one of the main sources of energy poverty within Europe, with low-carbon heating technologies replacement being one of the big concerns [30].

We define each country's 'relative investment intensity' as the annualised non-household energy infrastructure investment (starting from today's existing infrastructure) as a percentage of annual national GDP, which is used here as a proxy for the size of the economy of each country. We further define 'additional investment burden' on households as the difference between the modelled investment in household heating technologies and the historical level of expenditure on household appliances. We use data for household appliances since data for heating technologies are unavailable across Europe. Both are defined as a percentage of household income. A positive 'additional burden' means that the modelled household investment in heating technologies exceeds the historical household investment level in all appliances, which approximates an 'out-of-status-quo' situation. Both indices describe the impact that energy transition investment has on countries or households, respectively. The higher the value, the heavier the investment needed compared to the current economic capability. For a visual illustration of both indices, see figure 1.

Then, we observe how uneven the distributions of both indices between countries are. We compute the statistical variances for these indices across countries for each system design to quantify unevenness, yielding the two most even and the two most uneven system designs, in order to see system design distributive effects on both extremes.

This assessment method is applied to both disparity-unaware near-optimal European energy system designs and the four setups of system designs that we generate ourselves, as will be introduced in section 2.2. Detailed calculation formulas are outlined in the sections below. The methodology can be applied to the energy system results of other studies.

2.1.1. Distribution of per-country non-household infrastructure investment

Non-household technologies are the ones that we regard as mostly used in public spheres, usually involving investors such as institutional investors and corporations. Calculating this investment amount and comparing it to each country's GDP is used to estimate how much the national economy would be affected, positively or negatively, by the investment into a net-zero energy system. GDP as an index is chosen due to its wide application in estimating the size of the national economy and in evaluating the government spending across different sectors [31–33]. Despite various critiques on its accuracy and the limitations of such an indicator to measure a country's level of prosperity [34], it serves the purpose of initial screening of the results. Investments in non-household technologies are analysed for technologies of two sector categories: power-related and synfuel-related. The power-related technologies in the model are the following: onshore wind, offshore wind, utility-scale solar photovoltaic (PV), battery, biofuel combined heat and power (CHP), methane CHP, waste CHP, nuclear, combined cycle power plant, and AC and DC transmission. The synfuel-related technologies are the following: biofuel to diesel, biofuel to methane, biofuel to methanol, biofuel to liquids, electrolysis, hydrogen to liquids, hydrogen to methanol, hydrogen to methane, hydrogen storage, and direct air capture.

The calculation of the needed investment in energy technologies adopts a brownfield approach. Our consideration is that although the existing capacity today (as of 2025) may reach end-of-life by 2050, we assume that utility-scale plants, when retired, might be replaced with the same type of facility. This assumption does not affect countries where current renewable capacities are marginal compared to the 2050 deployment values, while for countries with substantial existing capacities, this assumption is made based on estimates on the consistency of policy trends towards decarbonisation, as well as the sunk time and administrative cost in the process of plant buildout. The sources of existing capacity of non-household technologies are listed in the supplementary material.

The investment is annualised, using equation (1).

$$\text{inv\_cost} = \text{dep\_rate} \cdot \text{cap} \cdot \text{cost\_cap} + \text{om\_annual} \cdot \text{cap} \tag{1}$$

where dep_rate is the depreciation rate, cap is the technology capacity, cost_cap is the investment cost of the technology, and om_annual is the fixed annual operational and maintenance cost. The depreciation rate is calculated with the following formula:

$$\text{dep\_rate} = \frac{i \cdot (1+i)^{L_{\text{tech}}}}{(1+i)^{L_{\text{tech}}} - 1} \tag{2}$$

where i refers to the interest rate, which is 7.3% as is assumed in Pickering *et al* [24], and L_{tech} refers to the lifetime of each technology. When analysing the system designs, each technology's total capacity is retrieved and subtracted by the existing capacity to calculate the yet-to-be-invested capacity. No further investment is needed if the existing capacity is larger than the model-indicated one. Otherwise, the investment cost is calculated with the yet-to-be-invested capacity of each technology. The investment into all non-household technologies is aggregated and divided by the country's annual GDP, yielding a percentage value that we name relative investment intensity. Such a calculation is performed for each country. We calculate the variance of this percentage of each country in one specific system design to evaluate the evenness in non-household technology investments. The equation is as follows:

$$\text{inv\_intensity}_c = \frac{\sum_{\text{tech} \in \text{NHT}_c} \left(\text{inv\_cost}_{\text{tech},c} - \text{ex\_val}_{\text{tech},c}\right)}{\text{GDP}_c} \tag{3}$$

where inv_intensity stands for relative investment intensity, NHT stands for non-household technologies in each country, and ex_val stands for the equivalent monetary value of the existing capacity of a certain technology.

We adopt the technology cost assumptions of Pickering *et al* [24], which mainly originated from the Danish Energy Agency (DEA) in Euros in 2015. We used the GDP value of each country in 2018, aligning with the weather year and demand data assumption. However, as the system is meant to be complete in 2050, and the cost assumptions are also predictions of 2050 costs, we may have underestimated the financial capability of countries, as the GDP has been chiefly growing for most European countries since 2018. We do not adjust the GDP values with purchasing power parity since the cost value uncertainty of DEA may already outweigh the effect of including more place-dependent installation costs. However, we acknowledge that further investigation is needed to obtain more accurate cost estimates differentiated by European country in the future [35].

2.1.2. Distribution of additional household heating investment burden

As households adopt decentralised heating technologies, especially net-zero compatible ones, we assume new investments are needed, which could pose financial challenges to low-income households if they were to bear all the costs. Here, we first identify household heating technologies, then calculate the investment needed for these technologies, and finally compare that to average household income to assess the additional burden. Average income is chosen to approximate the income level of residents in each country. Although the average value might not be the best representation of the general income distribution in each country, it is chosen due to data availability issues.

We classify heat pumps, biofuel boilers, methane boilers, electric heaters, and small heat storage as household heating technologies. All types of CHP, assumed as district-scale ones in the model, are non-household heating technologies. For each system configuration, we compute the additional household heating investment burden based on a greenfield approach. Namely, we do not account for the existing heating technology capacities in households. This choice is based on the consideration that data on existing capacity, technology type, state, and age are hardly available. The optimisation target time is 2050, so we can assume that existing heating systems will be at the end of their life at that time.

Now, we calculate the investment volume of household heating technologies. Considering that the assigned 'household-related technologies' are not only deployed in households but also in other settings such as commercial buildings, we assume the percentage of heating technologies invested by households is the same percentage of household heat demand compared to the total heat demand,

$$\text{hh\_heat\_inv\_share}_c = \frac{\text{hh\_heat\_demand}_c}{\text{tot\_heat\_demand}_c} \tag{4}$$

where the subscript c stands for country-specific, hh_heat_inv_share is the share of household investment in small heating technologies, hh_heat_demand is the sum of household heat demand in all time steps, and tot_heat_demand is the total heat demand, including household, commercial and industrial ones in all time steps. The investment volume of households on heating technologies in a country is therefore:

$$\text{hh\_heat\_inv}_c = \text{hh\_heat\_inv\_share}_c \cdot \sum_{\text{tech} \in \text{HHT}} \text{inv\_cost}_{\text{tech},c} \tag{5}$$

where hh_heat_inv_c is the investment into heating technologies for households in a country, $\text{inv\_cost}_{\text{tech}}$ is the investment cost of a certain technology, and HHT stands for the group of household heating technologies. The heat demand data is inherited from the workflow described in Pickering *et al* [24]. The heat demand of Icelandic households is assumed to be zero due to the wide deployment of geothermal heating. Therefore, Iceland is not included in the analysis of household heating technology. For small heat storage, we only account for energy costs (MWh) rather than power (MW).

Then, we calculate the annualised investment cost using technology cost assumptions, lifetime, depreciation rate, and the capacity given by the model, see equation (1).

We define the additional burden as the difference between the model-indicated investment level, characterised by the percentage of household income, and the highest historical expenditure level from 1994 to 2020 on household appliances from Eurostat [36],

$$\text{add\_burden}_c = \frac{\text{hh\_heat\_inv}_c}{\text{tot\_hh\_inc}_c} - \text{hist}_{\text{HHAp},c} \tag{6}$$

where HHAp stands for household appliances, tot_hh_inc stands for total household income for a country, and hist stands for the highest historical expenditure level as a percentage of household income.

2.1.3. Evaluating evenness

The evenness of investment, both in non-household technologies and household heating technologies, is calculated by the variance of the additional burden or relative investment intensity of all countries (in the former case, Iceland is excluded). We do not use the Gini coefficient because our data may include both positive and negative values, making it unsuitable for the Gini coefficient. Variance allows the scale of differences in additional burden to remain visible, as we believe the outliers are also of importance in this case. We calculate variance as follows:

$$\sigma^2 = \frac{\sum (X - \mu)^2}{N} \tag{7}$$

where σ^2 is variance, X is each value in a set, μ is the arithmetic mean value of the set, and N the number of values in the set. Here, a 'set' means the relative investment intensity or additional household investment burden of all countries in one specific system design. For each system design, we get one variance value.

Then, we compare that variance value between all system designs by calculating a normalised unevenness measurement. The variance of each system design is divided by the highest variance in all system designs in a certain setup, yielding a set of values from 0 to 1. Additionally, we employ two other indices to evaluate the distribution of relative investment intensity and additional burden for households, see section S5 of the supplementary material.

2.1.4. Other characterisations of energy system designs

We also characterise energy system designs with energy technology capacity per capita and the penetration of CHP. They are calculated as follows,

$$\text{cap\_pc}_{\text{tech},c} = \frac{\text{cap}_{\text{tech},c}}{\text{pop}_c} \tag{8}$$

where pc stands for per capita, $\text{cap}_{\text{tech},c}$ stands for the capacity of technology tech in country c, and pop_c stands for the population in country c.

For each country, the penetration of CHP is calculated as follows:

$$\text{CHP\_pen} = \frac{\sum_{\text{CHP\_tech},t} \text{heat\_flow\_out}_{\text{CHP\_tech},t}}{\sum_t \text{heat\_demand}_t} \tag{9}$$

where CHP_pen is CHP penetration rate, CHP_tech stands for each specific type of CHP, t is each time step in the model, heat_flow_out is the produced heat in TWh. This formula divides the total heat produced from all types of CHP by the total heat demand of a country in a year.

2.2. Energy system models

Here, we introduce in detail the configuration of the models that we analyse and run.

2.2.1. Model 1: disparity-unaware

We first analyse the 441 system designs from Pickering *et al* [24] (referred to as 'disparity-unaware system designs' hereafter), where one cost-minimising system design and 441 near-optimal system designs with diverse geographical distribution of technologies are presented. The model depicts the 35 countries in the European Network of Transmission System Operators for Electricity (ENTSO-E) network. In our analysis, we aggregate the sub-country level model results of 98 regions into 35 countries to perform our analysis based on the available data on income levels in these countries. Sub-country technologies and dynamics, such as low-voltage level distribution grid enhancement, are not covered by this model.

Pickering *et al* [24] use an optimisation-based sector-coupled energy system model with power, heat, and transport sectors. It assumes the energy demand of each modelled region in a time series, and allows choices for investments in energy technologies to meet that demand. Between regions, one can invest in power transmission lines to exchange electricity, while the model assumes synthetic fuels can be transported at no cost. The objective is to minimise the sum of the total investment and operational cost while meeting all energy demand at all times in all regions. It is a greenfield model, with the assumption of completely rebuilding the energy system around renewable technologies without any fuel imports from outside of Europe. This represents a long-term future system after a complete energy transition. Finally, MGA is applied to generate system designs that are as different to each other as possible within a 10% total cost increase. That difference lies in the technology capacities located in various model regions. Pickering *et al* [24] conclude that very different technology choices are equally technically feasible for Europe, with only small changes in total system cost. For more details, see the method and supplementary material of the original study.

2.2.2. Model 2: disparity-aware

Before adding endogenous disparity constraints, we modify model 1 in three ways. First, we use a national resolution version (which still includes all countries in ENTSO-E) to be compatible with the resolution of available data on income and GDP. Second, to better reflect real-world conditions and ensure the feasibility of additional constraints, we relax the constraint on waste usage, changing it from an equality to an inequality constraint. This means that the amount of waste used as fuel in each country does not have to be fully utilised, but rather, there is only an upper limit on its possible utilisation. Third, we adjust the demand for heavy and light transport to account for freight transport. Fourth, we added information about the existing capacities of technologies, such as onshore wind and solar PV, in each country in the model definition so that the resulting capacities would not go below the existing ones.

Then, to simulate limited external support in the transition and investigate potential transition bottlenecks, we introduce two constraints to ensure that the resulting investment plans do not go beyond the current economic capability of each country. The combination of the presence and absence of these two constraints forms four setups whose results can be compared against each other. First, to reproduce the disparity-unaware results in Pickering *et al* [24], we define the *Reference* setup with no additional constraints and reproduce the setup of model 1. Second, the *GDP* setup adds only the constraint that the relative investment intensity of non-household technologies should not exceed 5% of national GDP for each country. Third, the *Heat* setup adds only the constraint that the additional household heating investment burden should be non-positive. Finally, the *Combined* setup includes both constraints.

The first constraint, adopted by the *GDP* and *Combined* setups, is to limit the relative investment intensity of all countries simultaneously. The expression of this constraint is as follows:

$$\sum_{\substack{\text{tech}\in\text{NHT} \\ c}} \left(\text{inv\_cost}_{\text{tech},c} - \text{ex\_val}_{\text{tech},c}\right) \leqslant x \cdot \text{GDP}_c \quad (10)$$

where x is the modeller-imposed limit on relative investment intensity expressed as a percentage of the GDP, in this case, 5%. We ensure that each $\text{inv\_cost}_{\text{tech},c} - \text{ex\_val}_{\text{tech},c}$ will not be negative by enforcing a minimum capacity of each related technology in the model so that no term on the left-hand side is cancelled out. We choose 5% as a value, because it is slightly higher than the energy transition investments of the leading country in the world (i.e. China, 3.8% of GDP in 2023 [37]), and as a reference, some studies suggest that 5% of global GDP should be invested for the transition [38, 39]. This suggests that 5% is neither an unrealistic nor an overly conservative value to set as an upper bound for our constraint. Nevertheless, we run a sensitivity analysis to test our conclusions. We vary this threshold from 2.5% to 3% and then 10% in 1-percent increments. The results are reported in the supplementary material, section S4. The total system cost increases sharply when the threshold declines from 5% to 3% but flattens out when it gets past 8%.

The second constraint, adopted by the *Heat* and *Combined* setups, is to limit the additional household burden on investment in heating technologies,

$$\text{rel\_burden}_{\text{heat},c} = \frac{\text{hh\_heat\_inv}_c}{\text{tot\_hh\_inc}_c} - \text{hist}_{\text{HHAp},c} < 0. \quad (11)$$

We name system designs that comply with these two constraints as 'disparity-compatible', as they do not stray too far from the current economic capability of each modelled entity.

For each of the four setups, we run MGA to generate 70 near-optimal system designs. We utilise the 'SPORES' algorithm in the Calliope software, version 0.6.8. The total system cost relaxation is 10% above the minimal total cost (for details, see Lombardi *et al* [26]). For each setup, we first run 10 system designs with the `evolving_average` scoring method where we the algorithm helps expand the solution space, then run 60 system designs with `relative_deployment` where we maximise or minimise the capacity of targeted technology groups. These scoring methods are chosen to suit the purpose of expanding the solution space without technology targets and increasing spatial diversity respectively. Among the 60 system designs, we focus on maximising or minimising the deployment of 6 groups of technologies: variable renewable technologies, household heating technologies, bio-synthetic fuel technologies, hydrogen-synthetic fuel technologies, transmission technologies, and storage technologies. We run 5 system designs to maximise or minimise each technology group, respectively. This approach helps diversify the system designs while accommodating the computational resources at our disposal.

3. Results

3.1. Disparity-unaware methods produce highly uneven results

Figure 2 shows the result of our analysis for the disparity-unaware system designs. It is evident that while Europe-wide aggregated relative investment intensity and additional household burden cover a narrow and comparatively low range, this conceals a significant variability between individual countries. Even for the system design where the distribution of non-household energy investments is the most even between countries (marked blue in figure 2), there is still a difference of more than 10% between countries such as Great Britain and Germany. In the most uneven case, some countries' investment intensity reaches beyond 20%, and one even beyond 100%. In other words, more than the entire country's GDP would need to be spent on non-household energy investment every year until the transition is completed. As a reference, the most recent data on EU-wide average energy investments as a percentage of GDP is only 1.7% [40]. If we filter the 441 system designs with the criterion that no country should have investment intensity larger than 5%, no system design remains. Despite the wide range of solutions produced by MGA, a disparity-unaware model does not yield any system design compatible with today's magnitude of energy sector investments across Europe.

Concerning household heating investment, it is possible to have all countries below the baseline of historical expenditure on household appliances. Four of the 441 system designs fulfil this criterion. Yet,

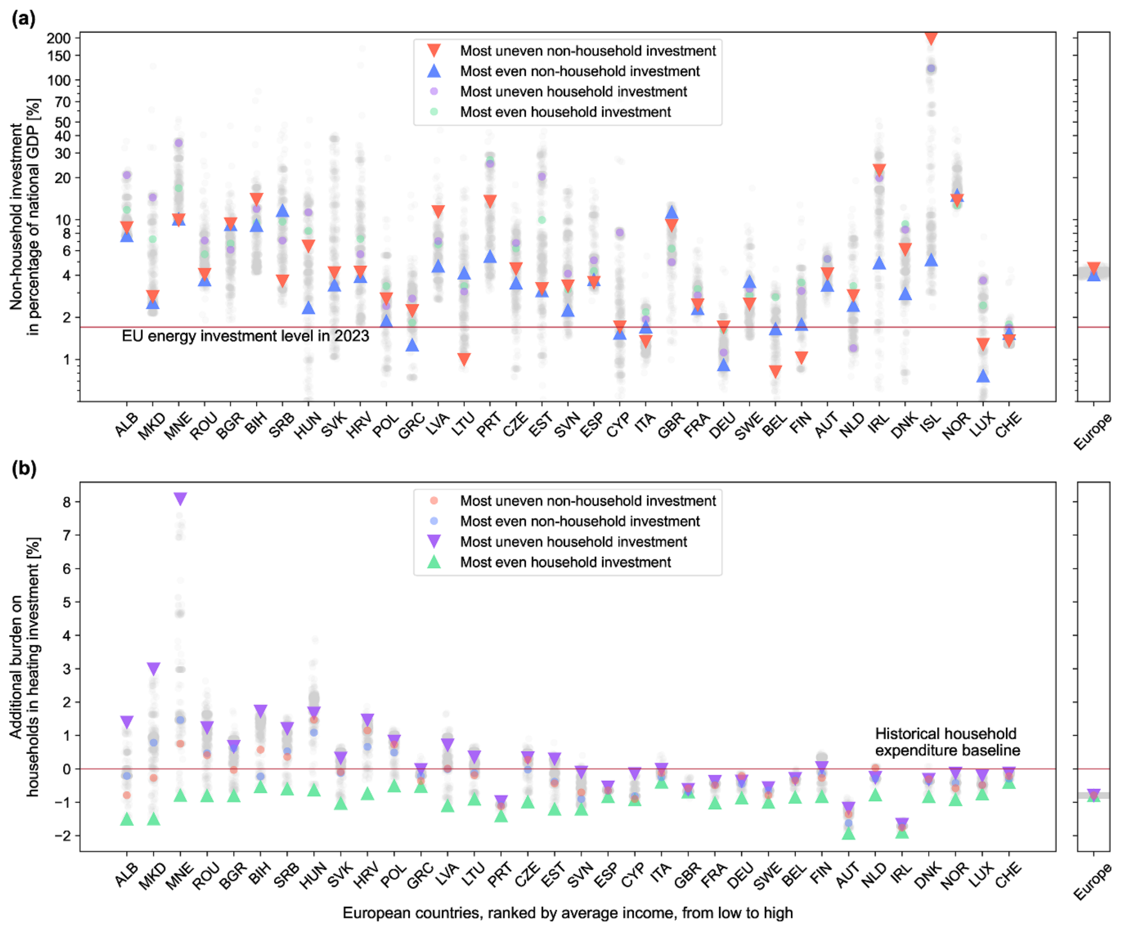

Figure 2. Investment distribution across countries in disparity-unaware system designs from non-household infrastructure and household energy investment perspectives. (a) Distribution of relative investment intensity across European countries of disparity-unaware 441 system designs. Each grey data point represents the relative investment intensity for one specific country in one specific system design. Out of the 441 system designs, the ones with the most even and uneven distribution of relative investment intensity are highlighted, as well as the most even and uneven in additional household heating burden. The same four system designs are highlighted in both panels. For example, the system design with the most even distribution of non-household energy infrastructure investment is shown in blue upwards-facing triangles, with an investment intensity of less than 10% of national GDP for Albania and more than 10% for Serbia. On the right side of the panel is the energy investment for the whole of Europe in terms of the percentage of Europe-wide GDP. (b) Distribution of additional investment burden on households in heating technologies across European countries in the same 441 system designs. Each grey data point represents the additional burden level for one specific country in one specific system design. The four system designs as in **a** are highlighted in the same colour. On the right side of the panel is the 'additional burden' calculated by the total modelled household heating technology investment for Europe, subtracted by the European average historical investment in household appliances, both in percentage of average European household income. Iceland is not included in this sub-figure as its heating demand is assumed to be zero in the model.

Table 1. Share of system designs with positive additional burden for countries in each income category.

Annual average income (EUR)	$<= 10\,000$	$10\,000 < x <= 20\,000$	$> 20\,000$
Share of system designs	85%	39%	4%

many other designs are highly uneven. The most uneven one in figure 2(b) shows that the highest additional burden can go up to 8% of average household income. While the most even one (shown in green in both panels of figure 2) makes sure that no countries experience additional burden for households, it requires non-household investment above 20% of GDP in some countries such as Ireland (27%) and Portugal (22%), highlighting that evenly distributing both household and non-household investment simultaneously may be mutually conflicting goals. We do not imply that more even system designs are better, but high unevenness might need clear justifications if decisions are to be made on the European level, especially relating to investment numbers as high as 20% of national GDP.

Moreover, as a general trend, households in lower-income countries on the left side of figure 2(b) tend to have a high additional burden in many system designs. Table 1 shows that countries with a lower

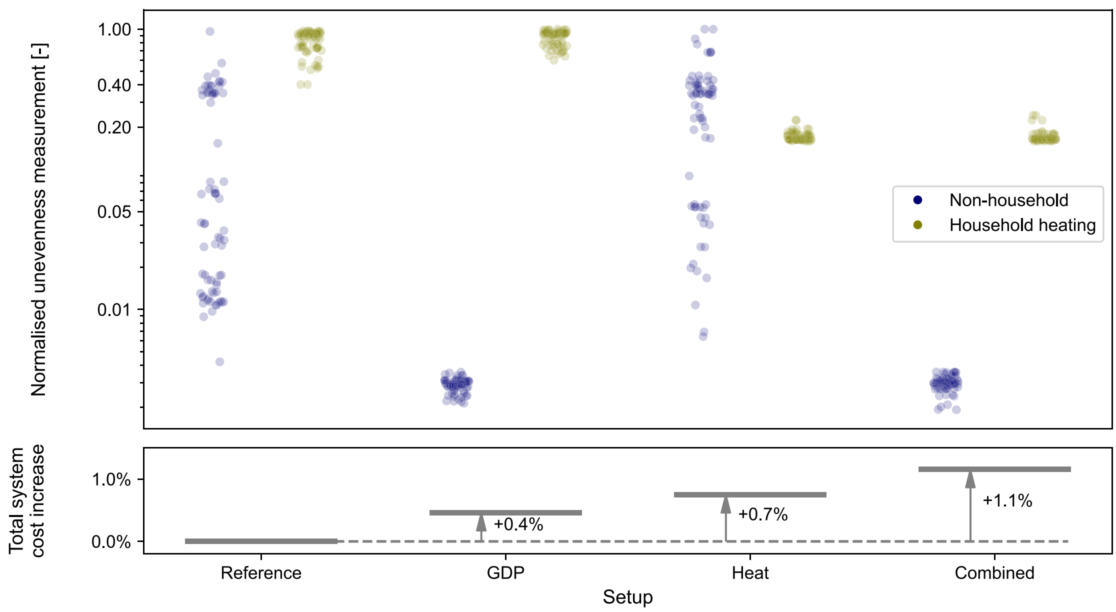

Figure 3. Unevenness reduction and the magnitude of total cost change across setups with different added constraints. For the top panel, on the *y*-axis is the unevenness measurement of relative investment intensity and additional household investment burden across European countries. The unevenness measurement, variance, is normalised by the highest value of the system design in all setups to better compare between setups. A lower unevenness value means higher evenness in a system design. All data shown on this graph are system designs produced by MGA, excluding the least-cost solution from which the MGA algorithm starts its search. All MGA system designs *within* one setup share the same total system cost, which is 10% higher than the minimal total cost. The system costs *across* four setups are different. The lower panel shows the total system cost increase of the corresponding system designs.

annual average income level have many more system designs in which they face a positive additional investment level. As the income disparity overtakes the heating demand between countries, a higher portion of household income has to be spent on heating technology investments in lower-income countries. This could lead to structural overburden of lower-income countries if the income disparity is not recognised and addressed by redistribution policies. Even if such an issue is identified when model users analyse the results, these results tend to imply that substantial subsidies are necessary to foster the transition. However, these subsidies are not always necessary because the presented system designs do not cover the full range of possible system designs. There are system designs where investment in household heating technologies for all countries remains compatible with the current level of household spending, as the following section demonstrates.

3.2. Disparity-compatible systems are possible with small cost increase

We plot the unevenness level in the two indices that we define for all system designs in our four setups in figure 3. First, we see that the *Reference* setup is comparatively uneven, as the 441 system designs analysed in the last section (see figure S1). Both constraints that we add contribute to a more even distribution while slightly increasing the total system cost. This reduction in unevenness is mainly due to the exclusion of extreme cases, such as a relative investment intensity of 175% of national GDP or an additional household investment burden of 8% of household income. We see from figure 3 that only 1.1% of the total cost increase is required to achieve such even system designs. From both panels of figure 4, we see that the order of magnitude of the unevenness is also largely reduced, compared to the panels in figure 2. While in disparity-unaware system designs, the relative investment intensity of countries can range from as little as 2% to as much as 20%, in our *Combined* scenario, it is limited between 0.5% and 5%. This range of investment relative to national GDP is more usually seen in current-day energy-related investments. On an international negotiation level, a 4.5% difference between countries might be more easily justified or agreed upon than an 18% difference.

Second, contrary to the observed trade-off between household and non-household investment evenness in the case of the disparity-unaware method, disparity-aware methods are able to achieve higher evenness in both indices simultaneously. The existence of a trade-off is merely the result of using a disparity-unaware model, highlighting the need to explicitly include disparity-awareness into the model formulation, with constraints such as the ones we introduce here. Although the disparity-unaware

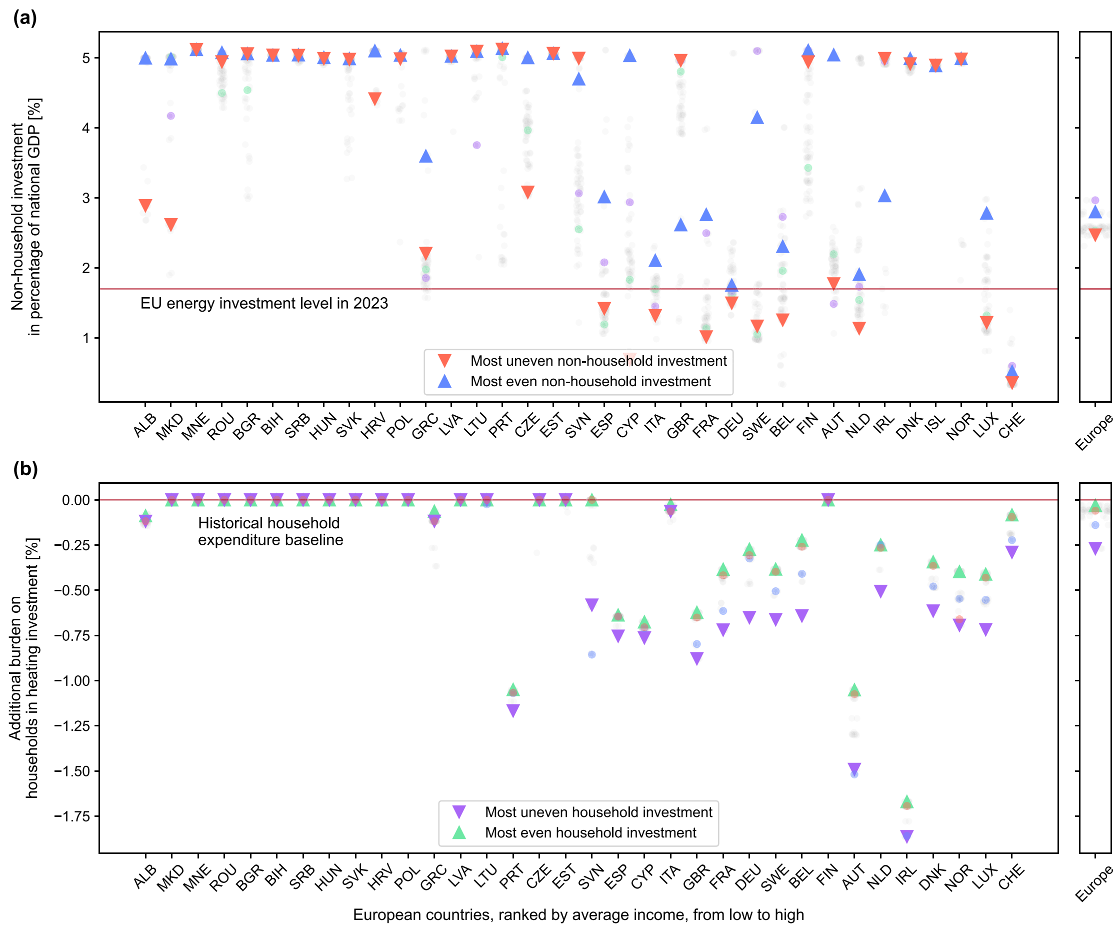

Figure 4. Distribution of relative investment intensities and additional household investment burden under both constraints in the *Combined* setup.

method might suggest that extensive subsidies targeting investment disparity are required, the disparity-aware method shows that this may not be technically necessary.

If we observe the distribution of each country's additional household investment burden, similar trends to figure 2(b) still exist. In most system designs, lower-income countries hit the 0% additional burden constraint, while higher-income countries are mostly below that. This phenomenon is further quantitatively assessed in section S5 of the supplementary material.

3.3. Power-sector investment can be evenly distributed across countries

Adding both constraints related to national GDP and household income does not significantly change Europe's total power-related technology capacities. As shown in figure 5(a), for example, there is no increase in PV generation capacity at the expense of wind across all setups. Instead, compared to the *Reference* setup, the combination of the disparity-aware constraints redistributes the capacities between countries in line with their economic capabilities.

As onshore and offshore wind are the technologies that contribute to most cases of high relative investment intensity for countries (see figure S2), we show the distribution of the average per capita wind capacity in Europe in figures 5(b) and (c). In the *Combined* setup, the average per capita wind capacity in wind-rich countries such as Iceland, Norway, and Ireland clearly falls. At the same time, Great Britain's slightly increases as it has a relatively high total GDP. Under the 'Max 5% GDP' constraint, countries with a high GDP can 'absorb' the capacity from other countries. For example, the average total wind capacity in Iceland decreases by 36.6 GW from the *Reference* to the *Combined* setup, but this is less than 7% of the wind capacity in Great Britain in any setup. This phenomenon might drastically change the picture for small countries like Iceland, which has a high wind capacity factor in the model and is thus favoured for wind technology expansion. Accordingly, in our *Combined* setup, the highest relative investment intensity in Iceland drops from 175% to 5%. Such a drop also implies a strategic adjustment in the energy investment for Iceland under different assumptions in the European

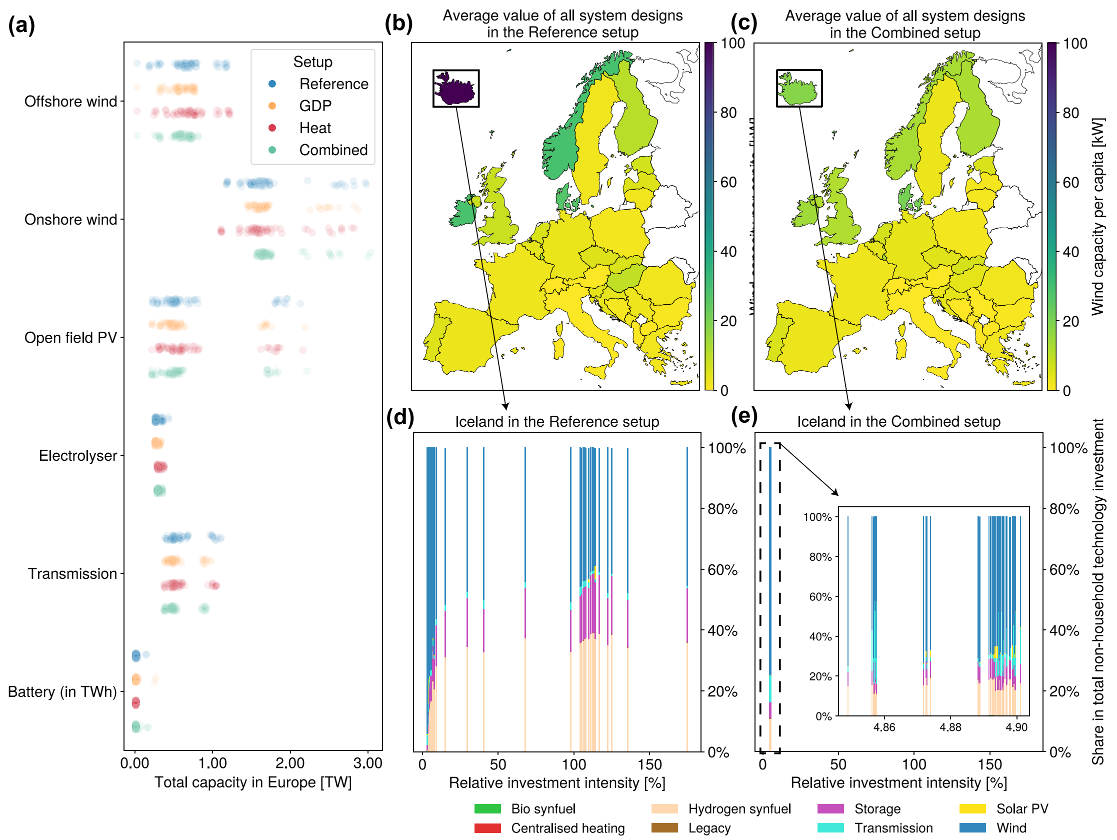

Figure 5. Power system investment across setups. (a) Total capacity of power system technologies in Europe across the four setups. (b) Average per capita capacity of wind capacity across system designs in the *Reference* setup, our results without any added constraint. (c) Same map as (b), but for the *Combined* setup, our results with both constraints added. (d) The relative investment intensity of Iceland in the *Reference* setup, where the *x*-axis signifies the relative investment intensity of a specific system design, and the *y*-axis is the share of each type of technology in the total non-household energy infrastructure technology investment. For example, in the system design where the relative investment intensity is 175%, the investment into hydrogen synfuel technologies amounts to roughly 40% of total non-household energy infrastructure investment, while storage is roughly 20%. (e) Same illustration as (d), but in the *Combined* setup.

energy system design: although the non-household investment is still dominated by the same four categories (wind, transmission, storage, and hydrogen synfuel), as shown in figures 5(d) and (e), a smaller portion is devoted to hydrogen synfuel and more to wind. This also happens for countries where solar PV starts to play a role in the technology mix in the *Combined* setup, such as Ireland.

3.4. Less affluent countries have less diverse technology choices

In disparity-aware setups, power system technology capacities are mainly redistributed within Europe without major changes to their Europe-wide total capacity. Heating technology capacities, however, do change in their total European capacity. This is particularly true for biofuel-powered CHP, as shown in figure 6(a). In the *Heat* and *Combined* setup, the limit on decentralised household heating investments necessitates investment into centralised heating for lower-income countries. Centralised heating utilises CHP as the only possible heat source in our model. As waste is fully utilised and synthetic methane has a high cost, biofuel is favoured as a CHP fuel. Since we assume a limited supply of sustainable and local biofuel, other biofuel-utilising technologies, such as biofuel to methane, are thus decreased. In turn, the capacity of hydrogen to methane generally increases to still satisfy the methane demand.

The change in total CHP capacities has a differentiated impact across European countries. Many lower- and middle-income countries, primarily concentrated in Eastern Europe, tend to have much higher shares of CHP in meeting their heat demand in the *Combined* setup, as shown in figure 6(c). Under investment-limiting constraints, these countries are ‘pushed to the corner’ in terms of their choices in technology investments: the relatively low household income level forces them into the centralised heating solution, but the ‘budget’ is limited due to the relatively low national GDP, leaving little space for investment in other technologies such as solar PV and wind. The example of Serbia in figures 6(d) and (e) shows that, under these model constraints, these countries have a much smaller set of energy investment options. Estonia could choose to develop hydrogen synfuel in some system designs

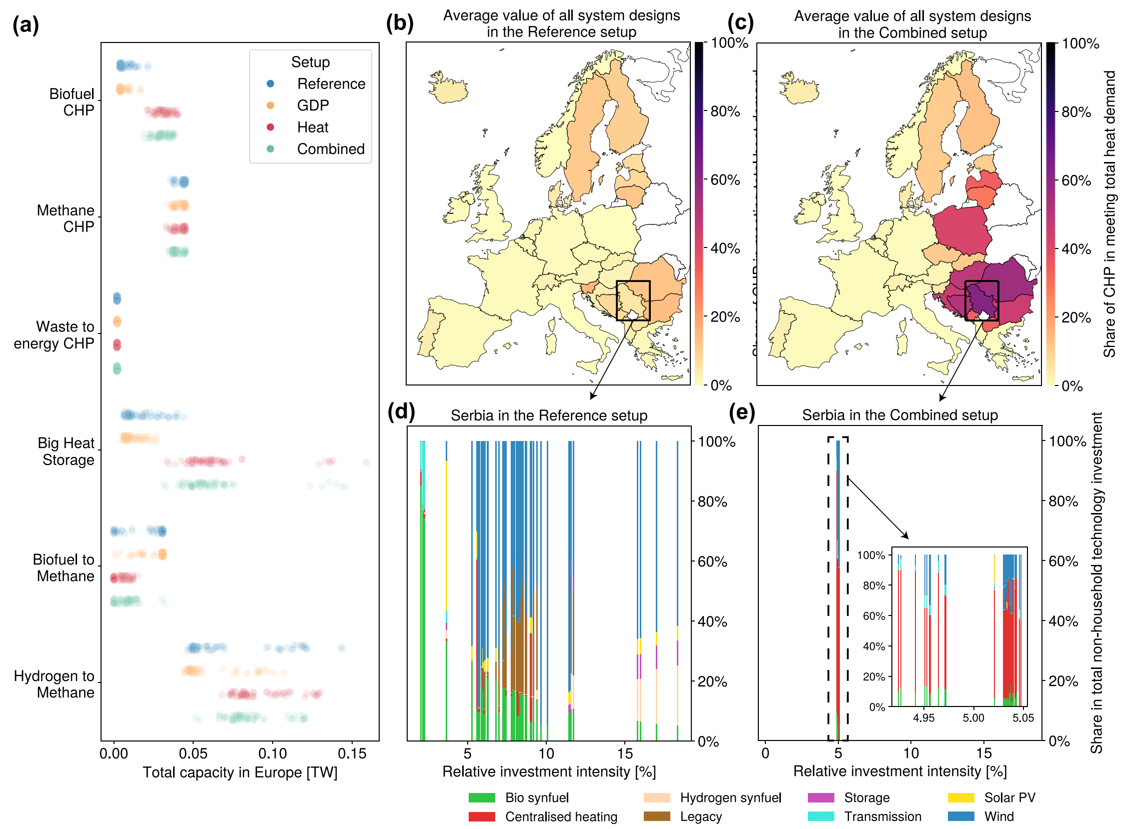

Figure 6. Heat technology investment across setups. (a) Total capacity of heating-related technologies in Europe across four constraint setups. (b) Average share of CHP in meeting the total national heat demand of all countries across all system designs in the *Reference* setup, our results without any added constraint. (c) Same map as (b), but in the *Combined* setup, our results with two constraints added. (d) The relative investment intensity of Serbia in the *Reference* setup, where the *x*-axis signifies the relative investment intensity of a specific system design, and the *y*-axis is the share of each type of technology in the total non-household energy technology investment. For example, for the system design with a relative investment intensity close to 16%, bio-synfuel amounts to roughly 5% of the total non-household technology investment. (e) Same illustration as (d), but in the *Combined* setup.

in the *Reference* setup, and Croatia could deploy some bio synfuel technologies, but this all becomes negligible in the *Combined* setup. Bulgaria, Bosnia and Herzegovina, Hungary, and Romania all experience a similar trend, as can be seen from figures S2 and S3. This implies that external investment support would be needed to enable them to 'escape' from this corner. On a different note, lower-income countries do not necessarily show a high CHP share, as Albania, the lowest-income country, does not have a high CHP share level. This is due to a combination of various factors, including the exceptionally low per capita heat demand level in the input data and a higher level of historical household appliance investments. Nevertheless, we regard household income level as an important factor to consider in energy system planning.

Note that the increased usage of biofuel CHP in the result does not translate into a necessity to use biofuel CHP in the real world, as the result is a combined effect of multiple model assumptions. More policy options could be available to satisfy household heating demand without overburdening households, such as subsidies for low-income groups. Nevertheless, this result demonstrates the significance of potential household burden and fuel stringency in the transition and, thus, the necessity of discussions informed by disparity-aware modelling methods for distributing expenditure between countries. The magnitude of external support depends on the choice in each particular country; if predominant centralised heating is regarded as suitable for a country, it might still be a good way to decarbonise without the negotiation and administrative efforts that redistribution requires.

4. Discussion and conclusion

In this study, we show that disparity-unaware models can produce results that tend to be disproportionate relative to the economic capability of involved actors. If this disproportionality is overlooked, policies based on model results may overlook potential transition difficulties since economically weaker groups are overly burdened. By making economic disproportionality visible and endogenising it in the model formulation, we show that disparity-aware models can produce system designs that are compatible with actors' different economic capabilities for a 1.1% increase in total system costs. This avoids the situation where some small countries are allocated a significant amount of technology capacity, which might be difficult to implement in real life. Using disparity-aware models may structurally affect the energy decision for these countries. Moreover, household income is a constraining factor in decentralised household heating investments. Many lower-income countries have to switch to centralised heating, CHP. If these countries are also comparatively limited in national GDP, they are left with limited technology choices in other energy sectors for achieving a decarbonised energy system.

Our findings confirm the conclusions of Sasse and Trutnevyte [21] that model results may risk sustaining regional inequalities. However, we find that this may only be true with disparity-unaware modelling methods. Disparity-aware methods can mitigate this danger. Our result shows 1.1% total system cost is minimally needed for making the system design disparity-compatible, which is roughly in line with the conclusion that a certain type of more even distribution, such as the one defined in this work, would not greatly sacrifice total cost efficiency [19, 20]. Our results also correspond to other studies that outline heating transition difficulties, such as investment into new, sustainable heating technologies in Central and Eastern European countries [30, 41]. We confirm studies that indicate mitigation policies may be more burdensome for lower-income countries [9], and that lower-income households would have higher expenditure increases [11].

This study aims to acknowledge potential transition bottlenecks in modelling studies that inform policy-making by making first steps to endogenise specific limiting factors. The results are informative in various ways. First, it can give an initial order-of-magnitude estimate of the differentiated financial challenges of the energy transition for each country, serving as part of the evidence for policy-making, alongside considerations such as administrative timelines, supply chain and labour availability. For example, if lower-income countries would like to transition without requiring residents to replace their heating devices, prior planning and coordination around district heating might be worth prioritising; otherwise, there might be financial aid needed to realise a decentralised heating decarbonisation. Second, on the European governance level, it helps estimate whether and to what extent redistribution policies should be enacted, such as the design of EU-level transition-related funding schemes. The Social Climate Fund is already a policy endeavour towards this matter. Additionally, for countries that might face high relative investment intensities, more focus could be placed on policies to encourage investments, such as derisking policies in lowering the cost of capital, and public investment from entities like the European Investment Bank. As the model does not endogenise practical factors besides investment and operational costs and technology efficiencies, the result is best understood as a first integration of distributive investment burden which can be refined with additional factors in future studies.

Our study has limitations that could be complemented by further research. First, we focus on investment to account for the upfront investment process. We do not focus on operational costs and future energy prices for now due to the uncertainty in fuel cost accounting in model results. We acknowledge that operational costs also play an important role in distribution issues and thus deserve further analysis in the context of energy equity. While not explicitly analysed here, we expect the incorporation of operational costs and fuel costs would further strengthen our argument about potential disparities, as electrification allows lower operational costs, but poses high upfront cost challenges for lower-income households. Second, we simplify the investment representation by using a uniform cost of capital and stationary income and GDP assumptions for all countries. Given the trend that financial risks tend to be higher in countries where average GDP is lower [35], the disparities would be further exacerbated with a more differentiated cost of capital. We believe the insights of this study would still hold even with more nuanced financial assumptions, but it is worth exploring effective investment strategies in greater detail [42]. We are also aware that GDP does not reflect the full picture of national fiscal or institutional capacities. We do not cover aspects such as public debt, sovereign borrowing costs, or fiscal rules, all of which are also highly relevant for renewable energy development. However, we discuss additional dimensions of national fiscal conditions in section S6 of the supplementary material, which could be picked up in future work.

Third, national average income data cannot capture intra-nation financial inequalities and thus can only serve as a first step to include more demographic information in models. Energy burden is multi-dimensional and related to various other social factors, such as home ownership, the rural-urban division, and identities such as ethnicity and gender. From an equity point of view, it is desirable that such aspects play a bigger role in models used for policy advice, especially smaller scale ones, such as municipality-scale models. We nevertheless believe the integration method, introduced in this work, could be useful also for smaller scale models. Fourth, we have examined the cross-country variance of investment burdens in this work, which is a distributional metric and cannot account for other aspects of justice such as procedural and recognition ones. To broaden the perspectives covered by the analysis, we also preliminarily examine the Atkinson index and conduct progressivity tests in section S5 of the supplementary material. These metrics could be complemented by more contextualised data on financial situations of nations or households, and additional statistical analyses.

Nevertheless, our methods could be applied and extended to cases outside of Europe on various geographical scales. Not only can this method be applied in the energy system modelling field, but it could also be adopted by the integrated assessment modelling studies, where economic disparity not only contribute to accounting for climate damage, but also for new infrastructure roll-out. Besides, where GDP and household income are not the most descriptive indices for acute social concerns, modellers can address different layers of inequality, such as accessibility and service reliability [43]. Our study highlights the potential importance of endogenising disparity in energy system models to plan the energy transition, as well as the necessity of redistribution mechanisms from both the national government and the EU level to ensure a smoother transition.

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Data availability statement

The external input data used in this study are attached in an .xlsx file as supplementary. Results of the model in this study are accessible at https://doi.org/10.5281/zenodo.15287742. Additional explanatory graphs are included in the Supplementary document in .pdf format.

All data that support the findings of this study are included within the article (and any supplementary information files).

Supplementary document 1 available at https://doi.org/10.1088/2753-3751/ae6b8f/data1.

Supplementary data 1 available at https://doi.org/10.1088/2753-3751/ae6b8f/data2.

Code availability

The model used in this study is accessible at https://doi.org/10.5281/zenodo.19706475.

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