

# Energy transition and social justice: Do renewable energy levies have an impact on income distribution and energy poverty?

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## Article

**Keywords:** Energy transition, social justice, renewable energy, income distribution, energy poverty JEL

Classification Nos.: D12, O33, Q41

**Posted Date:** August 11th, 2021

**DOI:** <https://doi.org/10.21203/rs.3.rs-754301/v1>

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# **Energy transition and social justice: Do renewable energy levies have an impact on income distribution and energy poverty?**

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## **Abstract**

Energy systems are decidedly the largest emitters of greenhouse gases. Therefore, transitioning them from fossil to renewable systems is a top priority for societies committed to reducing greenhouse gas emissions. However, such transitions involve substantial costs. In many cases, these costs are proportionally passed on to final energy consumers through levies on their electricity consumption. In our paper, we investigate the impacts of renewable support levies on social justice or, more specifically, on income inequality. For our study, we chose Germany where inflation-adjusted electricity prices for private households increased substantially because of such a levy for renewables. We base our analyses on representative household panel data with over 40,000 households from 2003 to 2018. Our results indicate that indiscriminate renewable support levies on electricity consumption increase income inequality and energy poverty. For our case in 2018, renewable support levies alone led to a relative increase of ~0.23% of the Gini coefficient and ~11.31% of the high cost low income (HCLI) energy poverty indicator measuring energy poverty intensity. Based on our findings, we propose a reform of the renewable support levy and analyze three options: (1) the abolition of the levy, (2) levies which are income-progressive proportionally to the income taxes, and (3) a high and flat levy in conjunction with an income-degressive compensation payment. Our ex-post analyses for 2018 indicate that a reformed levy system would have slightly decreased overall income inequality with relative decreases of ~0.23%, ~0.32%, and ~0.59% of the Gini coefficient for options (1), (2), and (3), respectively. But more importantly, such a system would have substantially decreased energy poverty by ~11.31%, ~30.45%, and ~31.45% for the HCLI energy poverty indicator for options (1), (2), and (3), respectively.

## **Keywords**

Energy transition; social justice; renewable energy; income distribution; energy poverty JEL Classification Nos.: D12, O33, Q41.

## Main text

With ~2.8 bn tons of global carbon dioxide (CO<sub>2</sub>) emissions in 2018, the energy sector is decidedly the largest emitter of greenhouse gases (GHG) in the European Union (EU 27) with a share of ~84.5%. Despite a reduction of CO<sub>2</sub> emissions in the energy sector by 20.9% in 2018 compared to 1990 levels, further efforts are needed to achieve the goals of the Kyoto Protocol and the even more ambitious Paris Climate Agreement. Therefore, the transition from fossil to renewable energy systems is a priority for societies committed to reducing GHG emissions. However, such fundamental transitions require substantial investment and financial efforts.

In the European Union (EU) alone, 23 of its 27 member states have introduced feed-in tariffs to attract sufficient investment in renewable energy sources (RES) as of 2019<sup>1</sup>. Through these feed-in tariffs, operators of renewable energy plants are remunerated with a prefixed premium for their renewable energy production, more or less guaranteeing the economic viability of their investments.<sup>2</sup> In many cases, the cost of the feed-in tariffs are proportionally passed on to final energy consumers through levies on their electricity consumption. By avoiding the financing of feed-in tariffs through public budgets, governments may circumvent increases of their national debts and, with that, negative impacts on debt ratings as well as interest rates.

The introduction of feed-in tariffs led to a substantial increase in the share of electricity from RES in Europe. From 2003 to 2018 the share increased by a factor of ~2.2 in EU27 from ~14.5% to ~32.2%, and most notably in Germany, where the share of RES on final electricity consumption increased by a factor of ~4.9 during this period from ~7.7% to ~37.8% (for details see Supplementary Dataset 1). However, RES support levies in Germany for residential electricity consumers increased by a factor of ~12.0 during the same period (in inflation-adjusted values). As a result, residential consumers, in particular, have been subject to substantial electricity price increases. From 2003 to 2018, final residential electricity prices increased by ~71.0% on average (~12.28 €-ct/kWh from ~17.19 €-ct/kWh). Of these, 37.1%-points (~6.37 €-ct/kWh) are attributable to the RES support levies alone (for details see Supplementary Table 1).<sup>3,4</sup>

In many cases, residential electricity consumers are faced with uniform RES support levies on energy consumption irrespective of their income situations. However, economic theory suggests that increases in prices of consumer goods or services impact consumers differently depending on their individual preferences and income situation<sup>5,6</sup>. Creedy<sup>7</sup> and García-García et al.<sup>8</sup> demonstrate that this principle also applies to electricity. The lower the consumer's income, the higher his or her relative share of income allocated for expenditures on electricity and vice versa. Therefore, electricity price increases pose a relatively higher burden on low-income households compared to high-income households<sup>9</sup>. In consequence, if increases in

electricity prices are extreme, income inequality, as well as energy poverty and, with them, (perceived) social injustice, might eventually reach levels that are unacceptable for society. In case increases in electricity prices are primarily due to the support of RES, such as in Germany, and the distribution of the costs for RES support is perceived as unfair, societal support for the transition from fossil to renewable energy systems will eventually be at risk, as demonstrated by Andor et al.<sup>10</sup>.

In our paper, we assess the impacts of uniform RES support levies on electricity consumption and social justice or, more specifically, on income inequality and energy poverty. For our analyses, we used representative micro census data of over 40,000 German households over 15 years (2003 to 2018) from the official income and consumption sample (ICS) to examine the socioeconomic impacts of substantial increases in residential electricity prices<sup>11,12</sup>. Based on our results, we propose an alternative regulatory scheme for the distribution of RES costs among residential electricity consumers with the goal of increasing social justice by mitigating income inequality and energy poverty.

### **Expenditures of private households for electricity**

On average, German households spent higher relative shares of their income on electricity with 2.3% in 2018 against 1.8% in 2003: This corresponds to a relative increase of 20.2%. Therefore, household incomes increased less in relation to residential electricity prices. However, a more in-depth analysis reveals that low-income households are more severely affected by electricity price increases than higher-income households (see Figure 1). Households in the first income-decile on average spent 4.5% of their income on electricity in 2018 and 3.6% in 2003 on average, which corresponds to a relative increase of 26.9%. In comparison, households in the last income-decile spent 1.0% of their income on electricity in 2018 and 0.9% in 2003 on average, which corresponds to a relative increase of only 14.1%. For further details on recent developments of electricity prices, see Supplementary Figure 1.

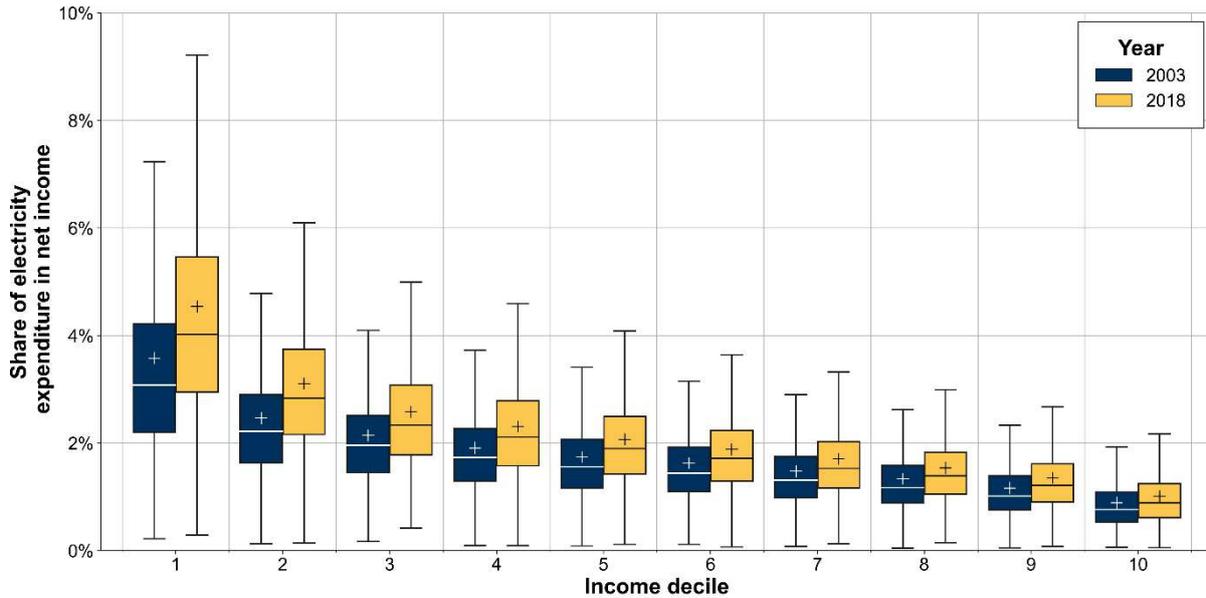


Figure 1: **Share of residential electricity expenditure in net income.** The values are calculated for the ICS data sample of the years 2003 and 2018. Private households are grouped into income deciles according to the OECD equivalence scale. The mean values are represented by “+”-markers. The whiskers are limited to 1.5 the interquartile range. Outliers are not plotted.

### Private households responses to an increase in the electricity price

Increases in electricity prices do not proportionally propagate to increases in electricity expenditures. Behind this discrepancy are adaptations of consumer behavior following such increases in prices. In general, and this includes electricity, higher prices are accompanied by lower demand and consumption. In economics, the relationship between changes in demand and changes in prices is mathematically expressed by the so-called price elasticity of demand, see equation (1).

$$\eta_p = \frac{\text{percentage change in demand for electricity}}{\text{percentage change in real electricity price}}. \quad (1)$$

Therefore, the price elasticity of demand can be interpreted as the relative change in demand (quantity) following a one percent increase in price. If the elasticity is -2, a one percent price rise leads to a two percent decline in quantity demanded.

The higher the (absolute value of the) price elasticity of demand, the more elastic a consumer's demand for a certain good or service, meaning the consumption of the good or service in question following an increase in prices (and vice-versa for decreases in prices). Demand with absolute price elasticities above one is considered elastic (relatively sensitive to changes in prices). In contrast, demand with absolute price elasticities below one is considered inelastic (relatively insensitive to price changes).

$$|\eta_p| \geq 1: \text{demand is elastic}$$

$$|\eta_p| < 1: \text{demand is inelastic}$$

Based on the micro-panel data of the ICS, we analyze the price elasticities of private households for the time period from 2003 to 2018. Details on our calculations can be found in the Methods section. The results are shown in Table 1.

Table 1: Estimated long-term price elasticities of demand of private households in Germany for the time period from 2003 to 2018.

	Income decile										
	1	2	3	4	5	6	7	8	9	10	Average
$\eta_p$	-0.3541	-0.4526	-0.5662	-0.5003	-0.5366	-0.5910	-0.6693	-0.6548	-0.6819	-0.6869	-0.5976

Absolute values of price elasticities of demand for electricity are lower than 1, indicating that residential demand for electricity can be considered inelastic. In general, our estimates for price elasticity of demand match those found in the literature<sup>13–18</sup>.

Our results indicate that the price elasticity of residential electricity demand varies with the available income of the household. Therefore, we conclude that private households respond differently to a change in the electricity price. Lower-income deciles (deciles 1 to 5) show an average price elasticity of -0.48 while it is -0.66 for higher-income deciles (deciles 6 to 10). This means that households with a low disposable income react the least to an electricity price increase, whereas the wealthiest households react the most to a price increase.

According to the economic theory of Slutsky<sup>19</sup>, the total overall effect of a change in consumption after a price change can be attributed to two distinctive causal effects. The first effect is the substitution effect (*SE*). It indicates the share of the total change in consumption which can be attributed to the substitution of the good or service in question with alternative solutions on the market (e.g., cheaper options), see equation (2). The second effect is the income effect (*IE*) and indicates the share of the total change in consumption which can be attributed to a change in purchasing power of the consumer's income, see equation (3). Prices are given as  $p$  and  $p'$ . The purchasing power is represented by the budget  $B$  and a fictional purchasing power resulting in the same utility after a change in prices from  $p$  to  $p'$  by  $B^{fictional}$ . Consumption quantities are given as function  $x(p, B)$ .

$$SE = x(p', B^{fictional}) - x(p, B) \quad (2)$$

$$IE = x(p', B) - x(p, B^{fictional}) \quad (3)$$

We divide the change in consumption that we observe in the micro-panel data of the ICS between the years 2003 and 2018 into a substitution and an income effect using the Slutsky equation. We additionally decompose the total effect into a share caused by the price increase and a share caused by the change in the household budget.

Figure 2 shows the effects of the observed change in consumption from 2003 to 2018 (for a tabular representation of the data see Supplementary Table 2). The substitution effect

consistently outweighs the income effect. Therefore, the reduction in electricity usage can be better explained by substitution with other goods than by a decrease in purchasing power. The substitution effect increases with household income. Whereas for the first income decile, the substitution effect accounts for ~67% of the total change in consumption, it goes up to 109% for the high-income kWh deciles (which is compensated by positive income effects). This indicates that high-income households can substitute electricity more easily compared to low-income households.

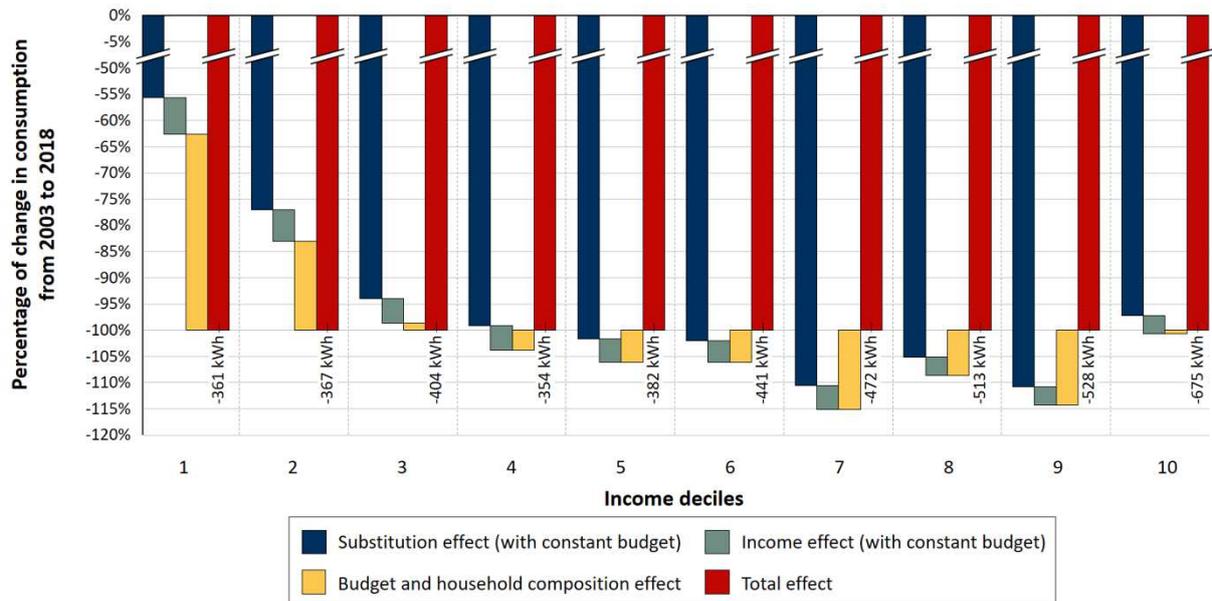


Figure 2: **Substitution, income, and total effect of the change in electricity consumption.** The effects are calculated for the period from 2003 to 2018. The effects occur due to the changes in the electricity price and disposable budget.

The income effect due to the price change is negative for all income deciles. Interestingly, the effect due to the change in household budget and composition is positive for all income deciles except for the three lowest income deciles where it is negative. This is due to the change in inflation-adjusted budgets from 2003 to 2018, which only decreased for these low-income households but increased for the medium- to high-income households. For the lowest income decile, ~37% of the decline in consumption can be explained by a reduction in purchasing power. In contrast, additional purchasing power increased consumption for the high-income deciles by ~15%. The results indicate that growing income inequality has strongly contributed to the decline in electricity consumption in low-income households.

The substitution capability of high-income households might be further incentivized by increasing the electricity price of these income groups. Goods such as more energy-efficient household appliances in particular or even appliances for a self-generation of electricity to become so-called "prosumers"<sup>20</sup> could then be increasingly purchased to substitute electricity consumption. Following this logic, high-income households should be more likely to make such substituting purchases. This argument is supported by the observed higher expenditures on

devices that influence energy efficiency and by the revenues from solar sales (cf. Supplementary Figure 2). Note that hypothetical decreases in electricity consumption because of energy efficiency gains might be partially compensated by the so-called rebound effect, cf. refs. <sup>21,22</sup>.

### The impact of the actual RES support levy on income distribution and energy poverty

The distribution of income is an essential socioeconomic indicator for social justice<sup>23</sup>. In this regard, the Gini coefficient is the most common indicator for (in-)equality in the distribution of incomes  $y_i$  in a society with a population of size  $n$  which can be calculated using equation (4)<sup>24,25</sup>.

$$G = \frac{\sum_{i=1}^n \sum_{j=1}^n |y_i - y_j|}{2n^2 \bar{y}} \quad (4)$$

We further apply the Atkinson index as inequality indicators to compare the distribution of wealth and assess the impact on social justice in terms of energy poverty<sup>26</sup>. We also derive an estimate of the change in social welfare  $W$  using the social welfare functions<sup>26</sup> and treating equivalent income as the measurement for utility. We consider the change in expenditure for electricity (due to a change in consumption) as additional income if negative and as a reduction in income if positive. We start with analyzing the impact of the actual RES support levy by simulating consumption behavior for the case of abolishing the RES support levy. For the Atkinson index, we use an equality-distributed equivalent measure (inequality aversion coefficient) of  $\varepsilon = 1$ . The results for the actual levy observed in 2018 are shown in Table 2.

Table 2: Results for the inequality indicators and social welfare estimates due to the actual allocation mechanism in 2018.

		Average equivalent income $\bar{y}$ [€]	Gini coefficient $G$	Atkinson index $A(\varepsilon = 1)$	$W = \bar{y}(1 - A)$ [€]
Actual levy	Absolute value	32,424	0.2888	0.1376	27,963
	Absolute value	32,490	0.2882	0.1368	28,046
No levy	Relative change compared to actual levy	0.20%	-0.23%	-0.58%	0.30%

Our results show that without RES support levies, the Gini coefficient and the Atkinson index would have been lower by 0.23% and 0.58% respectively in 2018. This indicates that the current allocation mechanism for RES cost slightly increases social inequality. However, note that the Gini coefficient calculated based on the ICS data tends to usually be underestimated as very-low- and very-high-income households are underrepresented in the data.

Table 3 shows the impact of the actual RES support levy on electricity poverty. The share of electricity-poor households ( $\alpha = 0$ ) would be lower by 1.05% to 9.57% without RES support

levy would. These findings are supported by our estimates for the poverty gap index ( $\alpha = 1$ ) and the squared poverty gap or poverty intensity ( $\alpha = 2$ ).

Table 3 Results for the energy poverty indicators before and after the introduction of our reform proposal

		2 x median share of expenditure			high cost / low income		
		FGT value ( $\alpha = 0$ )	FGT value ( $\alpha = 1$ )	FGT value ( $\alpha = 2$ )	FGT value ( $\alpha = 0$ )	FGT value ( $\alpha = 1$ )	FGT value ( $\alpha = 2$ )
<b>Real levy</b>	Absolute value	0.1253	0.0597	0.1152	0.1674	0.2224	0.7293
	Absolute value	0.1133	0.0499	0.1043	0.1656	0.1994	0.6468
<b>No levy</b>	Relative change compared to actual levy	-9.57%	-16.41%	-9.47%	-1.05%	-10.36%	-11.31%

Overall, the current allocation mechanism eventually led to higher income inequality and electricity poverty in 2018 compared to a hypothetical situation without RES support levies.

### Introducing reform proposals for the RES support levy

After having analyzed the impact of the actual RES support levy on income distribution and energy poverty in 2018, we introduce three alternative schemes of RES support levies for our analyses with the goal of reducing negative impacts on income inequality and energy poverty.

Our three analyzed alternatives are:

- Option 1: No RES support levies on electricity consumption,
- Option 2: a RES support levies which are income-progressive proportionally to the income taxes, and
- Option 3: a high and flat RES support levy in conjunction with an income-degressive compensation payment.

Option 1 might be realized by financing RES support payments through the State Treasury instead of through energy consumers via levies. The other two options 2 and 3 link RES support levies to disposable income with the goal of keeping negative impacts on income distribution and energy poverty low. Our reform proposal in option 2 relates the magnitude of the levy directly to the income tax rate resulting in a levy in 2018 ranging from 0.3 to 29.7 EUR-ct./kWh (excl. VAT) depending on the household's income. While this proposal might seem intuitive, it is likely to lead to difficulties in practical implementation as this requires the invoicing party (energy suppliers) to have knowledge about the customers' tax rates. To circumvent these practical issues, we propose another reform alternative for RES support with option 3. In option 3, the levy is identical to the levy of the highest income-decile in option 2 with 29.7 EUR-ct./kWh for all households. However, in option 3, the difference in expenditures for electricity to option 2 is compensated by the tax offices. An illustration of our two reform proposals (option 2 and option 3) for all income deciles can be found in Figure 3.

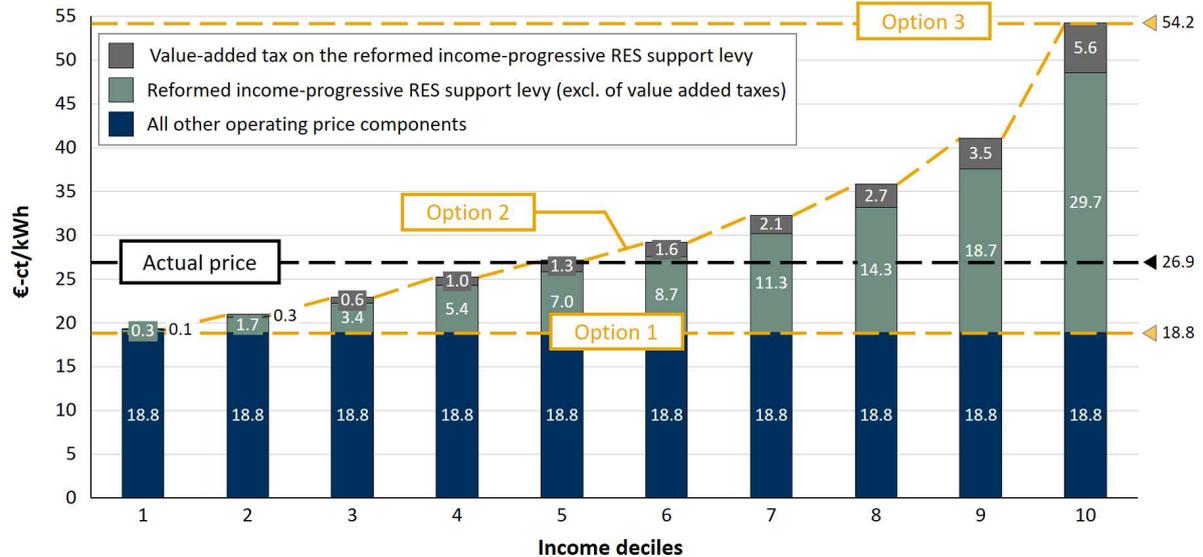


Figure 3: **Average residential electricity operating prices:** Private households are grouped into income deciles according to the OECD equivalence scale. The grey bars show the average operating price for 2018 without the RES support levy. The black dashed line shows the actual average operating price for 2018, including the RES support levy. The yellow dashed lines show average operating prices following our reform options 1, 2, and 3 for the RES support levy. In option 3, the difference in expenditures for electricity to option 2 is compensated by the tax offices.

### Impact of reform proposals for RES support levies on household electricity consumption, income distribution, and energy poverty

According to the theory of decreasing marginal utility of consumption, lower-income households have the highest additional gains in consumer surplus when increasing electricity consumption. Our RES support reform proposals would change consumption and expenditures of private households depending on their respective income. Therefore, we expect that our reform proposal would lead to an increase in social welfare.

Figure 4 shows the changes in electricity consumption for our three analyzed RES support options in comparison to the actual RES support levy in 2018. In option 1, the case of abolishing RES support levies, private households would consume markedly more electricity with 618 kWh on average per household and year (corresponding to an increase of ~23.2% or ~29.3 TWh in absolute numbers). In option 2, the income-progressive levy would not affect overall household electricity consumption. However, while lower-income households (income-deciles 1 to 5) would have a higher annual electricity consumption of 234 kWh on average per household, higher-income households (income deciles 6 to 10) would have lower annual consumption of 232 kWh on average per household and year. In our reform proposal in option 3, the high (flat) levy in conjunction with income-degressive compensation payments would lead to a strong decrease in overall annual electricity consumption of 811 kWh on average per household and year (corresponding to a decrease of ~31.1% or ~39.3 TWh in absolute numbers). The annual compensation payments would range from 0 € for the highest income-decile (no compensation) up to ~490 € for lower-income households.

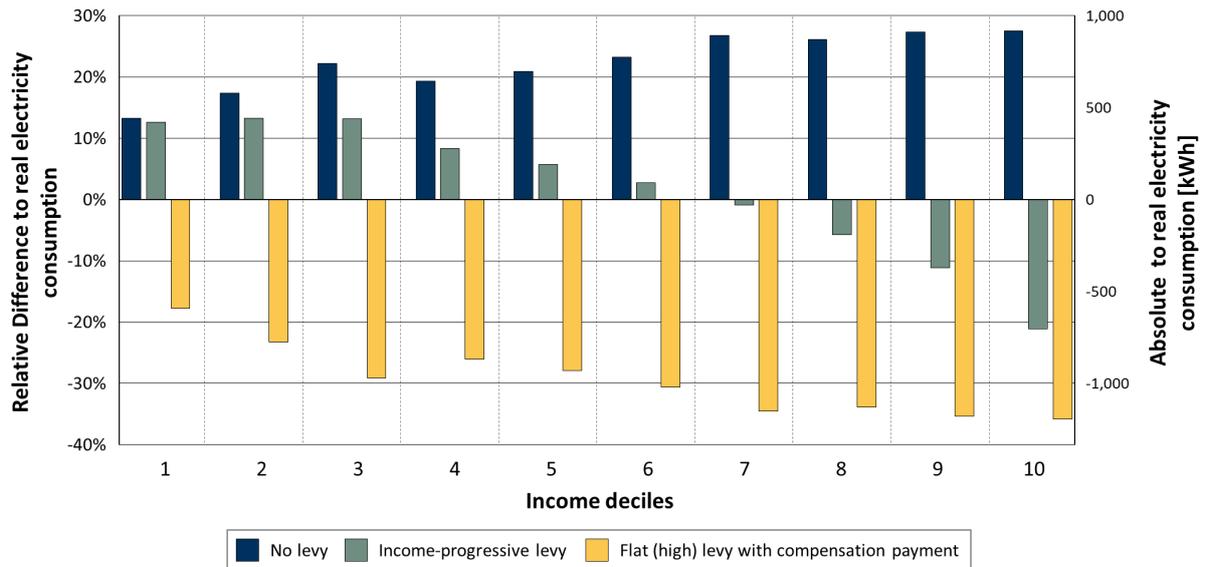


Figure 4: **Difference in electricity consumption for a reformed RES support levy.** Private households are grouped into income deciles according to the OECD equivalence scale. The blue bars show the case of the abolition of the RES support levy. The olive green bars show our reform proposal for an income-progressive RES support levy. The yellow bars show our reform proposal for a (high) flat RES support levy with an income-degressive compensation payment. Consumption values are compared to the electricity consumption observed for the actual RES support levy.

After having analyzed the impact of our reform proposals for RES support levies on expenditures and electricity consumption, we analyze their impact on income inequality and energy poverty. The derived values are shown in Table 4.

Table 4: Results for the inequality indicators and social welfare estimates before and after the introduction of our reform proposal

		Average equivalent income $\bar{y}$ [€]	Gini coefficient $G$	Atkinson index $A(\epsilon = 1)$	$W = \bar{y}(1 - A)$ [€]
<b>Actual levy</b>	Absolute value	32,424	0.2888	0.1376	27,963
<b>No levy (option 1)</b>	Absolute value	32,490	0.2882	0.1368	28,046
	Relative change compared to actual levy	0.20%	-0.23%	-0.58%	0.30%
<b>Income-progressive levy (option 2)</b>	Absolute value	32,429	0.2879	0.1365	28,001
	Relative change compared to actual levy	0.02%	-0.32%	-0.75%	0.13%
<b>Flat (high) levy with compensation payment (option 3)</b>	Absolute value	32,480	0.2871	0.1359	28,065
	Relative change compared to actual levy	0.17%	-0.59%	-1.20%	0.37%

For option 2, when adjusting the household incomes to the increased or decreased electricity expenditure after introducing the income-progressive RES support levy, the Gini coefficient decreases relatively by 0.32% and the Atkinson index by 0.75% compared to the actual support scheme. For option 3, the case of a (high) flat levy with an income-degressive compensation payment, the Gini coefficient decreases relatively by 0.59% and the Atkinson index by 1.20%. For both reform proposals, the results indicate that available income would be distributed more

equally among the population. As for social welfare, we observe an increase by 0.02% and 0.17%, respectively, when calculating based on the average income, and by 0.13% and 0.37%, respectively, when calculating based on the social welfare function in the Atkinson index.

Our results for the poverty measure calculations are shown in Table 5. They indicate that energy poverty would decrease drastically for both reform proposals compared to the situation with the actual allocation mechanism in 2018. For option 2, the income-progressive levy leads to a relative decrease of up to 38.06% in energy poverty depending on the indicator. For option 3, the flat (high) levy with compensation payments leads to a relative decrease in energy poverty of up to 34.64% depending on the indicator.

Table 5 Results for the energy poverty indicators before and after the introduction of our reform proposal

		2 x median share of expenditure			high cost / low income		
		FGT value ( $\alpha = 0$ )	FGT value ( $\alpha = 1$ )	FGT value ( $\alpha = 2$ )	FGT value ( $\alpha = 0$ )	FGT value ( $\alpha = 1$ )	FGT value ( $\alpha = 2$ )
<b>Actual levy</b>	Absolute value	0.1253	0.0597	0.1152	0.1674	0.2224	0.7293
<b>No levy (option 1)</b>	Absolute value	0.1133	0.0499	0.1043	0.1656	0.1994	0.6468
	Relative change compared to actual levy	-9.57%	-16.41%	-9.47%	-1.05%	-10.36%	-11.31%
<b>Income-progressive levy (option 2)</b>	Absolute value	0.0901	0.0370	0.0800	0.1609	0.1680	0.5073
	Relative change compared to actual levy	-28.14%	-38.06%	-30.61%	-3.85%	-24.46%	-30.45%
<b>Flat (high) levy with compensation payment (option 3)</b>	Absolute value	0.0945	0.0390	0.0788	0.1586	0.1682	0.4999
	Relative change compared to actual levy	-24.59%	-34.64%	-31.64%	-5.25%	-24.38%	-31.45%

## Conclusion

Andor et al.<sup>10</sup> have demonstrated that social justice in terms of burden-sharing for RES support cost is fundamental for the social acceptance of transitions towards more sustainable energy systems. However, we have demonstrated that lower-income households are most affected by electricity price increases including those caused by the introduction of RES levies. In contrast, we observe that higher-income households are less affected by price increases and that they substitute parts of their electricity consumption, most likely with more energy-efficient appliances or through self-generation of electricity.

Furthermore, our results indicate that the current allocation mechanism for the renewable energy support levy led to a substantial decrease in household electricity consumption of ~23.2% (or ~29.3 TWh) in 2018. However, the increase in electricity prices due to the flat RES support levy led to a slight increase in income inequality of ~0.23% of the Gini coefficient and a substantial increase in energy poverty of ~11.31% measured with the high cost low income (HCLI) energy poverty indicator. To circumvent these negative impacts, we propose to reform

the RES support levy mechanism. An income-progressive levy proportional to the income tax system would reduce income inequality with a relative decrease of  $\sim 0.32\%$  of the Gini coefficient as well as energy poverty with a decrease of up to  $\sim 30.45\%$  measured with the HCLI energy poverty indicator. However, energy service providers would need to have access to information on their customers' income which practically makes the implementation of such a system highly improbable.

Instead, we propose the introduction of a (high) flat levy in conjunction with an income-degressive compensation payment through the tax offices. Our results indicate that such a RES support levy system would reduce the electricity consumption of private households even further. Both, lower-income and higher-income households, would use part of their compensation payments for investments in energy efficiency improvements and self-generation increases where possible. Our analyses indicate that such a reformed RES support levy would lead to a reduction in income inequality of  $\sim 0.59\%$  of the Gini coefficient and a substantial reduction in energy poverty of up to  $31.45\%$  measured with the HCLI energy poverty indicator. Therefore, our reform proposal would improve social justice which would, in turn, increase social acceptance for a transition towards more sustainable energy systems as suggested by Andor et al.<sup>10</sup>.

While our study focuses on German households as a case, the question of how the cost burden of the sustainable energy transition should be allocated to the economy and the society is relevant for other cases. Our analyses can serve as an orientation for countries facing similar challenges with regard to the decarbonization of their energy systems.

In addition to a different distribution of costs of RES support payments within residential households, further investigation might be appropriate to assess the potential for a more socially just distribution of costs. In particular, further research might want to include industrial and commercial electricity consumers in their analyses on the distribution of costs of RES support payments.

## **Methods**

### **Data sample**

We employ pooled cross-sectional data across time collected through the official income and consumption sample (ICS) of the Statistical Office of Germany (Destatis) (as suggested by refs. <sup>27,28</sup>). The ICS is a household budget survey conducted every five years in Germany by its Federal Statistical Office. The data used is provided as scientific use-files that are reduced in the number of households to ensure the information provided is anonymous. We use this representative micro data to derive information about the electricity expenditures of 42,744 German private households for the year 2003 and 42,226 for the year 2018<sup>11,12</sup>.

## Grouping households into income deciles following the OECD equivalence scale

We define income classes as deciles according to the modified OECD equivalence scale, which weighs household members when calculating the net equivalent income<sup>29</sup>. The OECD equivalence scale assigns the primary income earner a weighting of 1.0, other household members at the age of 14 or more are given a weight of 0.5, and other household members below the age of 14 are assigned a weight of 0.3. The thresholds for the income deciles vary for each year in the ICS data set (for the income class definitions for each survey year, see Supplementary Table 3). Nevertheless, they are consistent in that, e.g., the fifth income class always represents the group of private households with an income right below the median but above the 40-percentile income of that year.

Table 6: Number of households grouped into income deciles and average OECD-factor of each income decile for the years 2003 and 2018.

		Income decile									
		1	2	3	4	5	6	7	8	9	10
2003	#households	4230	4237	4236	4251	4246	4232	4238	4232	4247	4228
	ØOECD-factor	1.42	1.58	1.64	1.66	1.70	1.70	1.72	1.68	1.63	1.55
2018	#households	4045	4105	4138	4129	4138	4143	4135	4137	4130	4135
	ØOECD-factor	1.22	1.39	1.45	1.50	1.55	1.59	1.57	1.58	1.55	1.50

## The electricity price development for residential end-users

Data for semi-annual electricity prices for residential end-users for 2003 and 2018 are taken from Eurostat. The database presents the average electricity price along five different consumption bands<sup>3</sup> (see Table 7).

Table 7: Methodologies of the Eurostat electricity consumption bands for private households<sup>3</sup>

Band	Old methodology (until 2007S1) consumption p.a.	New methodology (from 2007S2) consumption p.a.
DA	600 kWh	< 1,000 kWh
DB	1,200 kWh	1,000 kWh - 2,500 kWh
DC	3,500 kWh, including 1,300 kWh overnight	2,500 kWh - 5,000 kWh
DD	7,500 kWh, including 2,500 kWh overnight	5,000 kWh - 15,000 kWh
DE	20,000 kWh, including 15,000 kWh overnight	> 15,000 kWh

## Decomposing residential price responses into substitution and income effect

We apply the Slutsky equation to decompose the change in the electricity consumption of private households between the years 2003 to 2018 into two types of effects: the substitution effect and the income effect<sup>19,30</sup>. We assume that private households change their consumption due to a change in (1) the electricity price, (2) the price for non-electricity goods, and (3) the household disposable net income. We use this differentiation to evaluate how our proposed pricing regime for levy-based RES support will affect consumption in the residential sector. The substitution effect results from a change in the relative price of electricity versus non-

electricity goods. In this case, the goods are electricity (in our main interest) and all other consumer goods like food, clothing, household appliances, heating energy, health, etc. We use the relative increase in the consumer price index between 2003 to 2018 as the price increase for non-electricity goods. If the price of electricity is higher than that of non-electricity goods, then private households are forced to give up more of their non-electricity consumption to purchase electricity. The income effect is caused by the change in the purchasing power of the households' income when the prices for electricity and non-electricity goods increase while taking into account a change in income in the period under investigation.

We estimate the income and substitution effect for each income class using the private consumption expenditures as the income variable. Households spend their net income, in addition to private consumption, on income tax, insurance, and building up financial assets (see for example ref. <sup>12</sup>). We assume that private consumption expenditures better exemplify the budget  $B$  disposable for the goods to be analyzed (see Eq. (5)). To quantify the consumption preferences of a household for choosing between electricity and all other consumer goods (with quantities  $x_{el}$  and  $x_{oth}$ , respectively), we set up a Cobb-Douglas utility function  $U$  (see Eq. (6)).

$$B = p_{el}^{base} + p_{el}^{op} * x_{el} + p_{oth} * x_{oth} \quad (5)$$

$$U(x_{el}, x_{oth}) = x_{el}^{\alpha} * x_{oth}^{1-\alpha} \quad (6)$$

The exponents of electricity and all other consumer goods ( $\alpha$  and  $(1 - \alpha)$ , respectively) in the Cobb-Douglas utility function are derived from the observed consumption behavior between the years 2003 to 2018:

$$\Delta x_{el}^{Constant\ budget} + \Delta x_{el}^{Change\ in\ budget} = \Delta x_{el}^{Total\ effect} \quad (7)$$

$$\Delta x_{el}^{Constant\ budget} = \frac{\alpha * B_{2003} - p_{el,2018}^{base}}{p_{el,2018}^{op}} - x_{el,2003} \quad (8)$$

$$\Delta x_{el}^{Change\ in\ budget} = \frac{\alpha * (B_{2018} - B_{2003} + p_{el,2003}^{base} - p_{el,2018}^{base})}{p_{el,2018}^{op}} \quad (9)$$

$$\alpha = \frac{x_{el,2018} * p_{el,2018}^{op} + p_{el,2018}^{base}}{B_{2018} + p_{el,2003}^{base} - p_{el,2018}^{base}}. \quad (10)$$

The total effect of the price change from 2003 to 2018 on electricity consumption that we observe in the data,  $\Delta x_{el}^{Total\ effect}$ , can be interpreted as (1) a partial effect due to the change in consumption that would be observed if the budget, i.e., consumption expenditures, would have remained constant,  $\Delta x_{el}^{Constant\ budget}$ , and (2) a partial effect due to a change in budget and household composition,  $\Delta x_{el}^{Change\ in\ budget}$ . The budget in 2003 is represented by  $B_{2003}$ ,

the budget in 2018 by  $B_{2018}$ , the electricity consumption in 2003 by  $x_{el,2003}$ , and the electricity price in 2018 by  $p_{el,2018}$ . The resulting values based on the observed consumption behavior from 2003 to 2018 are shown in Table 8.

Table 8: Exponent of Cobb-Douglas utility function based on the change in consumption from 2003 to 2018

	Income decile										
	1	2	3	4	5	6	7	8	9	10	Average
$\alpha$	0.0386	0.0310	0.0274	0.0259	0.0247	0.0234	0.0216	0.0206	0.0193	0.0166	0.0230

The marginal utility  $MU$  of the utility function in Eq. (6) can be derived as:

$$MU(x_{el}) = \alpha * x_{el}^{\alpha-1} * (1 - \alpha) * x_{oth}. \quad (11)$$

Employing the values in Table 8, it can be shown that the marginal utility of increasing electricity consumption  $x_{el}$  is higher for low-income groups than for high-income groups.

Due to an increase in the prices for electricity and non-electricity goods, the slope of the budget constraint changes. To calculate the substitution effect, the budget is artificially increased so that the same quantities of electricity and non-electricity goods can be consumed. Using the Lagrangian method, we then derive a new optimal level of consumption. The substitution effect is equal to the difference in consumption between this new artificial optimal level of consumption and the original level of consumption in 2003.

The income effect is in general identified as the difference between the total effect and the substitution effect. By changing the budget from the artificially increased to its actual 2003 level, we derive the income effect caused by the price change. Finally, we adjust the budget to its 2018 level and derive the effect due to the change in the household decile's budget and household composition from 2003 to 2018.

### Calculation model for residential electricity price elasticities of demand

For calculating elasticity values, the midpoint method is used in contrast to the standard calculation of percentage changes. The advantage of the midpoint method is that it takes the average of two points in time as the initial value for computing the percentage change. This way, the calculated percentage change is identical for both directions of calculation<sup>31</sup>.

We adopt and extend the methodology applied in ref. <sup>14</sup>. This method determines the electricity consumption per household with the help of an average cost-expenditure function. It then applies the elasticity formula to the consumption and price values of the different years. We extend this method in two aspects:

- (1) We split the average cost of electricity into a base price and an operating price. Electricity tariffs in Germany are composed of a fixed cost component paid monthly or annually (base price) and a variable cost component that is charged per consumed

kWh of electricity (operating price). Levies and surcharges are part of the operating price. We, therefore, base our analysis of price elasticities of residential electricity demand solely on the operating price.

- (2) We decompose the change in consumption into an effect caused by the price change and an effect due to a change in the household budget and household composition. We base the calculation of the price elasticities of demand solely on the effect caused by the price change.

In Eq. (12), our method is applied for calculating the long-term price elasticity from 2003 to 2018, where  $\eta_p$  represents the price elasticity of demand,  $x_{el}$  the consumption quantities, and  $p_{el}^{op}$  the inflation-adjusted operating prices for electricity:

$$\eta_p = \frac{\frac{(x_{el,2018} - x_{el,2003})}{(x_{el,2018} + x_{el,2003})} \cdot \frac{(\Delta x_{el}^{Constant\ budget})}{(2 * x_{el,2003} + \Delta x_{el}^{Constant\ budget})}}{\frac{(p_{el,2018}^{op} - p_{el,2003}^{op})}{(p_{el,2018}^{op} + p_{el,2003}^{op})}}{\frac{(p_{el,2018}^{op} - p_{el,2003}^{op})}{(p_{el,2018}^{op} + p_{el,2003}^{op})}}} = \frac{\frac{(\Delta x_{el}^{Constant\ budget})}{(2 * x_{el,2003} + \Delta x_{el}^{Constant\ budget})}}{\frac{(p_{el,2018}^{op} - p_{el,2003}^{op})}{(p_{el,2018}^{op} + p_{el,2003}^{op})}}{\frac{(p_{el,2018}^{op} - p_{el,2003}^{op})}{(p_{el,2018}^{op} + p_{el,2003}^{op})}}} \quad (12)$$

In a first step, we exclude those households from the ICS data sets that show electricity expenditure values of zero. Further, it is necessary to differentiate between electricity expenditures and heating electricity expenditures as some of the households surveyed in the ICS rely on electric heating as their primary heating system (denoted by the variable "main type of heating energy"). Electricity employed for heating is subject to a differing electricity rate, usually cheaper than the one for residential electricity. We determine the share of residential electricity expenditures in total electricity expenditures by dividing the mean electricity expenditures of non-electric heating households by the mean electricity expenditures for electric heaters. This ratio (~51% in 2003 and ~49% in 2018) is then used to compute the residential electricity expenditures  $e_{el}$  of households that rely on electric heating. Eq. (13) shows the calculation for a household  $h$  of the ICS 2018:

$$e_{el} = \begin{cases} e_{el}^{total} * 0,4907, & \text{for } h = \text{houshold with electric heating} \\ e_{el}^{total}, & \text{for } h = \text{houshold with other types of heating.} \end{cases} \quad (13)$$

Next, we assign to each household a corresponding average cost of electricity. Following ref. <sup>14</sup>, we first transform the consumption intervals into expenditure intervals and then set up a linear average cost-expenditure function for each interval. For the first half of 2018, the resulting function is:

$$c_{el}^{2018S1}(e_{el}) = \begin{cases} -0.00040864e_{el} + 0.569764429, & 0 \leq e_{el} < 581.35 \\ -0,00006218e_{el} + 0.368347232, & 581.35 \leq e_{el} < 1,120.13 \\ -0,00001146e_{el} + 0.311540600, & 1,120.13 \leq e_{el} < 2,795.00 \\ -0,00001062e_{el} + 0.309177312, & 2,795.00 \leq e_{el} < 4,000.50 \\ 0.266700000, & e_{el} \geq 4,000.50. \end{cases} \quad (14)$$

Cost-expenditure functions for the other time periods can be found in Supplementary Equation 1 and Supplementary Equation 2. By applying the cost-expenditure functions, each household is assigned its average cost of electricity  $c_{el}$  in €/kWh depending on its electricity expenditure  $e_{el}$  in €/year. Thereafter, we derive the electricity consumption  $E_{el}$  in kWh by dividing the electricity expenditures by the corresponding average cost. The equivalent electricity consumption per household is again calculated according to the OECD equivalence scale, which is also suitable for electricity consumption, as shown in ref. <sup>18</sup>.

In a second step, we estimate average base prices and operating prices (2-part tariffs, see ref. <sup>32</sup> for more details). For this, we set up a regression model as:

$$e_{el} = \beta_{BP} + \beta_{OP} * x_{el}. \quad (15)$$

Using the initial estimation for the electricity consumption per household  $x_{el}$  from the first step and consumer electricity expenditures  $e_{el}$  as reported in the ICS data set, we calculate a first guess for the base price  $\beta_{BP}$  and the operating price  $\beta_{OP}$ . We then iteratively recalculate first  $x_{el}$  and then  $\beta_{BP}$  and  $\beta_{OP}$  until the difference in  $x_{el}$  between two iterations converges to zero. The resulting prices for the years 2003 and 2018 are reported in Table 9. The regression summaries for the two year are shown in Table 10.

Table 9: Average base price and operating price for residential electricity in Germany in 2003 and 2018 (in nominal prices).

	Base price [€/a]	Operating price [€-ct/kWh]
<b>2003</b>	93.01	14.56
<b>2018</b>	122.77	26.91

Table 10: Regression summary for the OLS models for estimating base and operating prices for the years 2003 and 2018.

$e_{el} = \beta_{BP} + \beta_{OP} * x_{el}$										
	2003					2018				
	Coeff.	Std. err.	Pr(> t )	Conf. interv.		Coeff.	Std. err.	Pr(> t )	Conf. interv.	
				[0.025	0.975]				[0.025	0.975]
intercept	93.0111	0.014	0.000	92.984	93.038	122.7660	0.018	0.000	122.731	122.801
$x_{el}$	0.1456	4.04e-06	0.000	0.146	0.146	0.2691	7.06e-06	0.000	0.269	0.269
R-squared	0.99997					0.99997				
Adjusted R-squared	0.99997					0.99997				

Finally, the inflation-adjusted electricity prices are computed with the help of the consumer price index with the basis year 2003. Lastly, we apply the midpoint method (see Eq. (12)) to

compute the elasticity values for each income class and across all income classes.

### **Developing and analyzing the reform proposals for an income-dependent allocation mechanism for the renewable energy support levy**

As an alternative to the currently uniform RES support levy for all residential consumers, we propose (1) an income-progressive allocation mechanism and (2) a (high) flat levy with an income-degressive compensation payment. Both proposals are designed analogously to the income tax system in Germany. The German income tax system works based on a progressive income tax. Under this system, the marginal tax rate increases up to a threshold value, the maximum tax rate (which for private individuals, i.e., natural persons, is currently at 45% according to the German Income Tax Act in effect in 2021). The resulting shares of the total income tax revenues (including solidarity surcharge) per income decile range from 0.02% (income decile 1) to 48.15% (income decile 10)<sup>33</sup>, meaning that the tenth income decile accounts for about half of all income tax paid by private individuals (excl. corporate bodies). We expect an income-progressive levy to be challenging to implement in practice, as energy suppliers would need to have information on their customers' income tax ratios. Therefore, we introduce our second reform proposal. Here, the actual flat levy is initially raised to a high level, and the additional expenditure compared to the first reform proposal is compensated by an income-dependent payment.

For developing an income-progressive RES support levy, we reallocate the €8.74 bn in RES support revenues that were contributed in 2018 from private households. We adopt the calculation for income taxation, transfer it to the RES support levy, and apply it to the ICS data. Based on extensive research, we processed 45 entries in the ICS data set to calculate the taxable income for each household individually. We then applied the income tax formula for 2018 (see Supplementary Table 4) to derive household-specific income tax rates. The resulting average income tax rates per income decile range from ~1% to ~27%.

To give an example, if a household's income is taxed at 25%, then the household must contribute  $k * 25\%$  of its income as RES support levy, where  $k$  is a constant scaling factor for all households that ensures that the total revenues of the RES support levy remain equal to the revenues in 2018. As the new RES support levy (inclusive of value-added taxes) changes the operating price, consumption changes likewise according to the respective price elasticity. Consequently, this results in new total RES support revenues. We repeat the calculation until the new RES support revenues converge towards the actual RES support revenues in 2018.

The new electricity consumption is calculated using the price elasticities. We make the assumption that the consumption that would have occurred in 2018 after (1) the abolition of the RES support levy and (2) the introduction of the reform results from an adjustment of consumption based on long-term price elasticity. We make use of the advantage that the

midpoint method works in both directions. The midpoint method is rearranged as shown in Eq. (16) to calculate first the consumption for the private household sample in 2018 that would have occurred in 2003 and then the new consumption in 2018, where  $x_{el}$  and  $p_{el}^{op}$  represent the electricity consumption and the electricity price, respectively. The results are shown in Supplementary Table 5.

$$x'_{el} = x_{el} * \frac{p_{el}^{op'} * (1 + \eta_p) + p_{el}^{op} * (1 - \eta_p)}{p_{el}^{op'} * (1 - \eta_p) + p_{el}^{op} * (1 + \eta_p)} \quad (16)$$

The second reform proposal builds on the first. The calculated income-dependent levy for the tenth income decile is set as the flat levy for all deciles. Again, the new operating price changes consumption according to the respective price elasticity. The compensation payments are defined as:

$$e_{el,i}^{comp} = (p_{levy}^{max} - p_{levy,i}) * (1 + VAT) * x'_{el} * \beta_{scaling}, \text{ for } i \in [1, \dots, 10], \quad (17)$$

where  $e_{el,i}^{comp}$  is the compensation payment for an income decile  $i$ ,  $p_{levy}^{max}$  the (high) flat levy for all income deciles,  $p_{levy,i}$  the income-progressive levy of income decile  $i$  (calculated in the first reform proposal), and  $VAT$  the value-added tax rate. The parameter  $\beta_{scaling}$  ensures that no additional federal budget is required to finance the compensation payments. Due to the compensation payment, the disposable income is increased. The additional income is partly spent on electricity which again increases consumption and results in an iterative process to find an equilibrium state.

### **Evaluation of the impact on social justice and energy poverty for different allocations of the costs of feed-in tariffs**

We assess the impact of

- (1) the current allocation of the support mechanism for renewable energy sources among private households,
- (2) the allocation according to an income-progressive RES support levy, and
- (3) the allocation according to a (high) flat RES support levy combined with an income-degressive compensation payment

on social justice and energy poverty based on the inequality of income distribution and energy poverty measures. For a detailed study on the definition and the origin of energy justice, refer to ref. <sup>34</sup>. The most common way to measure income inequality is the Gini coefficient<sup>23,25</sup>. The Gini coefficient indicates the degree of inequality of the distribution of income, e.g., in a country or region, according to household equivalence incomes<sup>35</sup>. The calculation of the Gini coefficient is based on the so-called Lorenz curve<sup>36</sup>. The Lorenz curve represents the relationship between the cumulative percentage of the population (x-axis) and the cumulative share of the

income of this population (y-axis). The Gini coefficient ranges from 0 to 1, where a value of 0 represents an equal distribution of income and a value of 1 represents a maximum of unequal distribution. In 2018, the Gini coefficient for Germany was at ~0.311, while in 2013 it was at ~0.297<sup>37</sup>.

In addition to the Gini coefficient, we also use the Atkinson index to measure income inequality<sup>26</sup>. The Atkinson index is a normative social welfare-based measure of inequality. The measure depends on the assumed social aversion to inequality following the concept of risk aversion. Using the Atkinson index, an equally distributed equivalent (EDE) income can be derived. The EDE income represents the income that would lead to the same level of welfare as the actual income distribution if each individual received it. The difference between the mean income and the EDE income reflects the welfare loss due to inequality.

In ref. <sup>38</sup>, the authors find that for Germany in 2012, the flat RES support levy has a regressive effect and increased the Gini coefficient by 0.56% and the Atkinson index by 1.43% for an inequality aversion of  $\varepsilon = 1.0$ . For 2017, authors in ref. <sup>39</sup> find that the RES support levy increased the Gini coefficient by 0.97% and the Atkinson index by 2.05-2.43%.

We further investigate the impact of the current allocation mechanism and of our reform proposals on a modified form of energy poverty, which we call electricity poverty, using the two times median share poverty line and the high cost / low income (HCLI) poverty line, as suggested by ref. <sup>28</sup>. The two times median share poverty line considers those households as electricity-poor whose electricity expenditure shares on income accounts for more than twice the median value. In comparison, the HCLI poverty line considers those households as electricity poor whose electricity expenditure shares are higher than the median value while, at the same time, having an income below 60% of the median. We use equivalized incomes and expenditures according to the OECD equivalence scale for our analysis. We then derive measures for electricity poverty using the FGT index from Foster et al. <sup>40</sup>

$$P_{\alpha} = \frac{1}{N} \sum_{i=1}^q \left( \frac{e_i - z}{z} \right)^{\alpha}$$
, where  $N$  is the number of households,  $q$  the number of households below the poverty line,  $e_i$  the expenditure or expenditure shares for energy services (in this case only electricity), and  $z$  the poverty line. We use values of  $\alpha = 0$  (headcount ratio),  $\alpha = 1$  (poverty gap index), and  $\alpha = 2$  (squared poverty gap, measuring poverty intensity).

## Data availability

The income and consumption samples (Einkommens- und Verbrauchsstichprobe) from 2003 and 2018 can be purchased from <https://doi.org/10.21242/63221.2003.00.04.3.1.0> and <https://doi.org/10.21242/63211.2018.00.04.3.1.1>. The source data for the figures within this paper and other findings of this study are available from the corresponding author upon request.

## Code availability

The python code for generating the study results will be made available on GitHub upon publication.

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**Acknowledgments**

This research was funded by RWTH Aachen University.

**Author Contributions**

A.P. conceived and designed the research. J.P. implemented the methodology and carried out the analysis. A.P. and J.P. analyzed and interpreted the data. J.P. wrote the first draft of the manuscript. S.S. contributed to the implementation of the methodology and the interpretation of the data. R.M. contributed to the interpretation of the data and to the revision of the manuscript. A.P. revised and edited the manuscript. A.P. provided institutional and material support for the research.

**Competing Interests statement**

The authors declare no competing interests.

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