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The undervalued quality-of-life benefits of demand-side energy and climate strategies

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Climate mitigation strategies are mainly evaluated in terms of emissions reductions and economic costs, yet their wider effects on quality of life may strongly shape public support. Here we assess how different supply-side and demand-side energy and climate strategies in buildings, transport, and industry can affect quality of life. We use numerical energy system simulation models to quantify impacts on six quality-of-life dimensions across eighteen countries and compare these with results from representative surveys in Brazil, China, and the Netherlands. Survey respondents value multiple quality-of-life dimensions including health, energy security, employment, income, environmental conditions, and equity, confirming the relevance of a wider framing for climate mitigation beyond carbon dioxide emissions and Gross Domestic Product. Across modeled indicators, both strategy types are associated with overall quality-of-life improvements, while demand-side strategies tend to score better across a broader set of dimensions. Survey results show that people generally expect both strategy types will improve quality of life and view them as acceptable. Providing information on modeled quality-of-life outcomes improves these evaluations. These findings highlight the value of incorporating quality-of-life considerations into climate policy making.

Given the urgency of rapid and inclusive energy transformation and climate action, changes in both energy supply and demand are critical for timely deep decarbonization. Above all, the transformation must also advance more sustainable and equitable societies. Forward-looking scenario analyses of energy transitions predominantly adopt global, national, or, at best, aggregated sub-national perspectives. Critically, such approaches often neglect the role of individuals, households, and other economic agents (firms, institutions) as central actors and stakeholders in these transitions.

Most available climate mitigation scenarios center on technological shifts to low- or zero-carbon options in energy supply, while devoting limited attention to demand-side options, despite the considerable mitigation potential of the latter[1–3]. Demand-side strategies, like active and shared mobility, offer large opportunities for emissions reductions that generate multiple and intertwined environmental and social benefits, including reduced air pollution and enhanced accessibility and affordability of services.

Analyzing the benefits of demand-side strategies offers new impetus for valuing climate change mitigation, and has been prioritized by recent scientific literature, as well as the Intergovernmental Panel on Climate Change[4]. Looking at wider benefits can circumvent tradeoffs between climate objectives and broader developmental goals[5]. Benefits beyond climate can render mitigation strategies also more appealing to both policymakers and the public. Yet, prevailing policy-making—frequently informed by the assessment schemes outlined above—prioritize climate mitigation strategies that are cost-effective and politically viable. This approach often relegates non-climate benefits as secondary considerations ("co-benefits") or addresses them only incidentally.

To address these limitations, we need to broaden the analytical scope beyond traditional cost-effectiveness frameworks toward a more comprehensive evaluation of impacts of mitigation strategies on quality of life or wellbeing[6–11]. We contribute to closing this knowledge gap by assessing how demand- and supply-side strategies impact (*objective*) societal quality of life,

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as well as their perceived (*subjective*) impacts on individual quality of life, which have been largely overlooked. Notably, subjective evaluations may diverge from objective assessments, particularly in contexts characterized by information asymmetries or limited understanding of expected impacts[12].

Individuals' evaluations of climate mitigation strategies are likely shaped by their perceived impacts on personal quality of life. When individuals anticipate negative consequences on their quality of life from a given strategy, public support can decrease, even to an extent inhibiting their implementation[13–15]. Perceptions of quality-of-life impacts are also likely to be widely heterogeneous[16].

Here we address the following research questions:

(1) How does ambitious climate action, including strategies aimed at reducing resource use, affect quality of life? Can such strategies simultaneously enhance wellbeing for all, and specifically for the most deprived or vulnerable populations?
(2) How do demand-side strategies compare to those focused on transforming energy supply (i.e., supply-side strategies) in terms of their impacts on quality of life?
(3) Which dimensions of quality of life related to climate mitigation strategies do individuals subjectively value most?
(4) Do (objective) quality-of-life impacts of mitigation strategies and their (subjective) evaluations by individuals differ across different contexts?
(5) To what extent does providing information on the objective impacts of different climate mitigation strategies influence their perceived quality-of-life (QoL) impacts and acceptability?

To capture different contexts, we perform our analysis for a range of countries to identify possible commonalities as well as context-specificities. We especially aim to provide a deeper exploration of the solution space associated with changes in energy demand, with special focus on how such transformations intersect with quality of life and by comparing demand-side to supply-side strategies that yield identical emissions reductions.

Results and discussion

Quality-of-life impacts of climate change mitigation strategies

The wellbeing impacts of the six illustrative, prototypic climate change mitigation strategies (see Table 1) can be examined based on each major quality-of-life indicator separately (Fig. 1), and in their aggregate (Figs. 2 and 3, see also Supplementary Notes SN-2-3 for more detail). Note that all indicators have been renormalized to a base case = 100, where an increase in values (>100) indicates quality-of-life improvements, while lower values (<100) indicate a deterioration compared to the base case. For the aggregation, we first report an unweighted mean across the six indicators studied (see Fig. 1). For the three countries covered by our surveys, we also report the weighted mean across the quality-of-life dimensions, considering respondents' importance ranking of different well-being dimensions.

As can be seen from Fig. 1, all six climate strategies generally lead to improvements across all quality-of-life indicators, albeit to differing degrees. The smallest improvements can be seen in the indicator disposable household income net of energy costs, which increases only slightly (up to 1% increase over the base case and thus not discernible in Fig. 1), followed by improvements in terms of mortality declines resulting from lowered PM2.5 emissions (quality-of-life indicators improve up to 3% compared to the base case, also difficult to discern in Fig. 1). More impactful changes relate to improvements in energy security (lower vulnerability) as well as to equity (reductions in the difference between the energy costs of average compared to the poorest quintile households).

Large impacts can also be observed for energy sector job creation, though the trends are varied: three strategies yield large positive employment effects (strategy m_1 yielding an increase in energy jobs by 50% due to the dual impacts of vastly expanding renewable electricity generation and the development of an entire new infrastructure for production and transport/distribution of hydrogen to industrial high-temperature uses). Also noteworthy are two "demand reduction" strategies t_2 (modal split towards public transport) and m_2 (less materials use via recycling, lightweighting, digitalization), both of which lead to absolute declines in energy use and correspondingly lower energy sector jobs. Although our analysis was restricted to energy supply and use-related jobs, and the demand shifts of the t_2 and m_2 strategies are likely to increase jobs in the public transport and materials recycling sectors (for which no data were available), it is unlikely that these not yet estimated job impacts would counterbalance completely the job losses from a scaled-down energy supply sector. This highlights the need for sustainability and quality-of-life analyses to always carefully consider both winners and losers from climate change mitigation strategies, even if at first glance and in the aggregate, they appear as win-win solutions.

Figure 2a, b report the (6 dimensions) aggregate quality-of-life impacts for the six climate mitigation strategies. The boxplots summarize the statistics and dispersion of impacts across our sample of 18 countries. Figure 2a shows the results for all six quality-of-life indicators, while Fig. 2b shows the results for five indicators, excluding the energy jobs indicator, which, due to data limitations, could offer a partial view of employment impacts in the energy sector only, but not in other sectors affected by the strategies analyzed. The employment QoL dimension also received a lower ranking in the importance ranking in all three countries for which we were able to perform empirical surveys. It is particularly noteworthy to observe that, excluding considerations of employment, there is a persistent and noticeable trend that demand-side strategies (the sectorial _2 scenarios) outperform supply-side strategies (_1 scenarios) in terms of positive quality-of-life impacts.

Figure 3 illustrates, with the aggregate (6 indicators) snowflake diagram, the heterogeneity of the quality-of-life impacts of the 6 strategies examined across the 18 countries. It is noteworthy that quality-of-life impacts are generally positive across the board for all countries, but the magnitude of positive impacts varies between countries. From the countries analyzed, the largest quality-of-life gains from climate mitigation strategies would arise in the USA, South Africa, India, Canada, Italy, Brazil, and China. As such, our analysis suggests a positive conclusion for policy: framing the climate change mitigation conversation around quality of life could break political stalemates where the perception often persists that costs and benefits of climate strategies differ systemically between developed and developing countries. Our results indicate that developing countries stand to benefit as much, if not more, in terms of increased quality of life from well-crafted mitigation strategies.

Robustness of results

The impacts of climate mitigation strategies on quality of life are sensitive to the choice of indicators considered in the analysis (see Fig. 2a, babove) as well as to numerical uncertainties underlying the indicators used. To test the robustness of our results, we have performed an extensive sensitivity analysis via combinatorial analysis as well as a systematic shock analysis (see also Supplementary Notes SN-2-3).

The results of the combinatorial analysis are shown in Fig. 4. They exhibit a clear pattern of dominance across the different strategies depending on how many indicators are considered simultaneously. Specifically, the demand-side strategies in transport and buildings emerge as the most robust "winners" for their positive quality-of-life impacts. Strategy t_2 performs best when considering fewer indicators (winning 3 times with single indicators and dominating with 9–10 wins for pairs and triplets). As more indicators are considered together and the assessment becomes more comprehensive, strategy h_2 performs increasingly superior, eventually becoming the sole winner when all 6 indicators are considered simultaneously. Strategy m_1 shows some strength with fewer indicators (3 wins for both single and pairs), but its positive scoring diminishes as more indicators are considered. Noteworthy, strategies t_1, h_1, and m_2 never achieve the highest rank in any combination. However, when considering the combinatorial analyses of individual countries, strategies t_1 and t_2 emerge on top in several instances, without however one strategy clearly outperforming the others (see SN-2-3). Therefore, whenever a portfolio of (as opposed to single or very limited) strategies for climate mitigation is undertaken, the advantage of demand-side policies becomes clearer.

Table 1 | The six alternative prototypic climate mitigation strategies analyzed

Transport (passengers)		Buildings (heating/cooling)		Materials (industry)	
t_1	t_2	h_1	h_2	m_1	m_2
Transport electrification via EVs	Modal shifts to public transport, walking and cycling	Heating via electric heat pumps	Thermal retrofits, changed thermostat settings	Substituting fossil energy with H_2 in high-temperature applications in industry	Reduced demand for materials via recycling, longer use and lightweighting

Each strategy yields a 10% reduction of national-level CO_2 emissions.

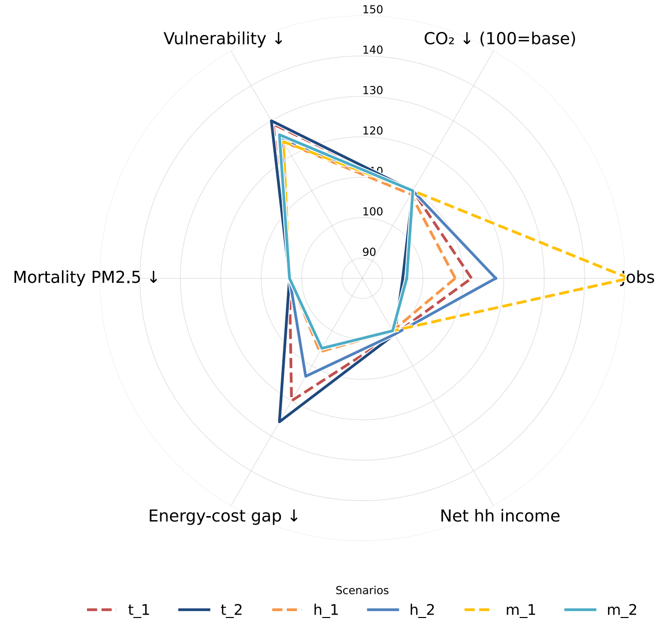


Fig. 1 | Six quality-of-life impacts of six climate change mitigation strategies that each achieve a −10% reduction in CO_2 emissions. Normalized index with 100 = base case (2019), values >100 indicating improved quality of life, numbers <100 indicating decreased quality of life. Indices are unweighted means of a sample of 18 countries accounting for close to 75% of global energy-related CO_2 emissions. For an explanation of the illustrative 6 strategies, see Table 1. t transport, h households, m materials; strategies ending with "_1" (dashed lines) are the supply-side strategies, and strategies ending with "_2" (solid lines) are the demand-side strategies.

The sensitivity of the results with respect to numerical uncertainties in QoL indicators are discussed in greater detail in Supplementary Notes SN-2-3. Varying individual QoL indicator values systematically by ±10% across all 18 countries impacts the aggregate QoL impact of the different strategies analyzed, with the resulting distributions represented graphically as "violin plots" (see Figs. SM-2-3-2 and SM-2-3-3 in the Supplementary Information). The impact of numerical uncertainty is largest for the m_1 strategy across all quality-of-life indicators, suggesting lower confidence in its ranking when considering numerical uncertainty in the analysis. Importantly, the relative ranking of strategies turns out to be robust vis-à-vis numerical uncertainty in the analysis. In particular, the demand-side h_2 strategy outperforms the supply-side h_1 strategy across all quality-of-life indicators, considering both positive as well as negative deviations in their impact parameters. Meanwhile, under numerical uncertainty, the supply-side strategies t_1 and m_1 tend to outperform their demand-side equivalents t_2 and m_2; however, as discussed above, the positive ranking of these strategies is less robust when considering the uncertainty of which and how many of the quality-of-life indicators are included in the assessment.

Considering both of our robustness tests (i.e., our different uncertainty analyses), the evidence points to a clear advantage in terms of climate mitigation strategy impacts on quality of life: strategy h_2, reducing heating energy demand of buildings via improved insulation and changing thermostat settings, outperforms other strategies in most settings.

Subjective assessment of quality-of-life dimensions and impacts

Supplementary Notes 3 provides a detailed overview of the survey results. Results first show that respondents consider all six quality-of-life dimensions important when evaluating mitigation strategies (see Fig. 5), clearly indicating that people across the three countries generally agree that multiple quality-of-life dimensions should be considered in climate strategy assessments, next to the dominant cost-effectiveness assessments.

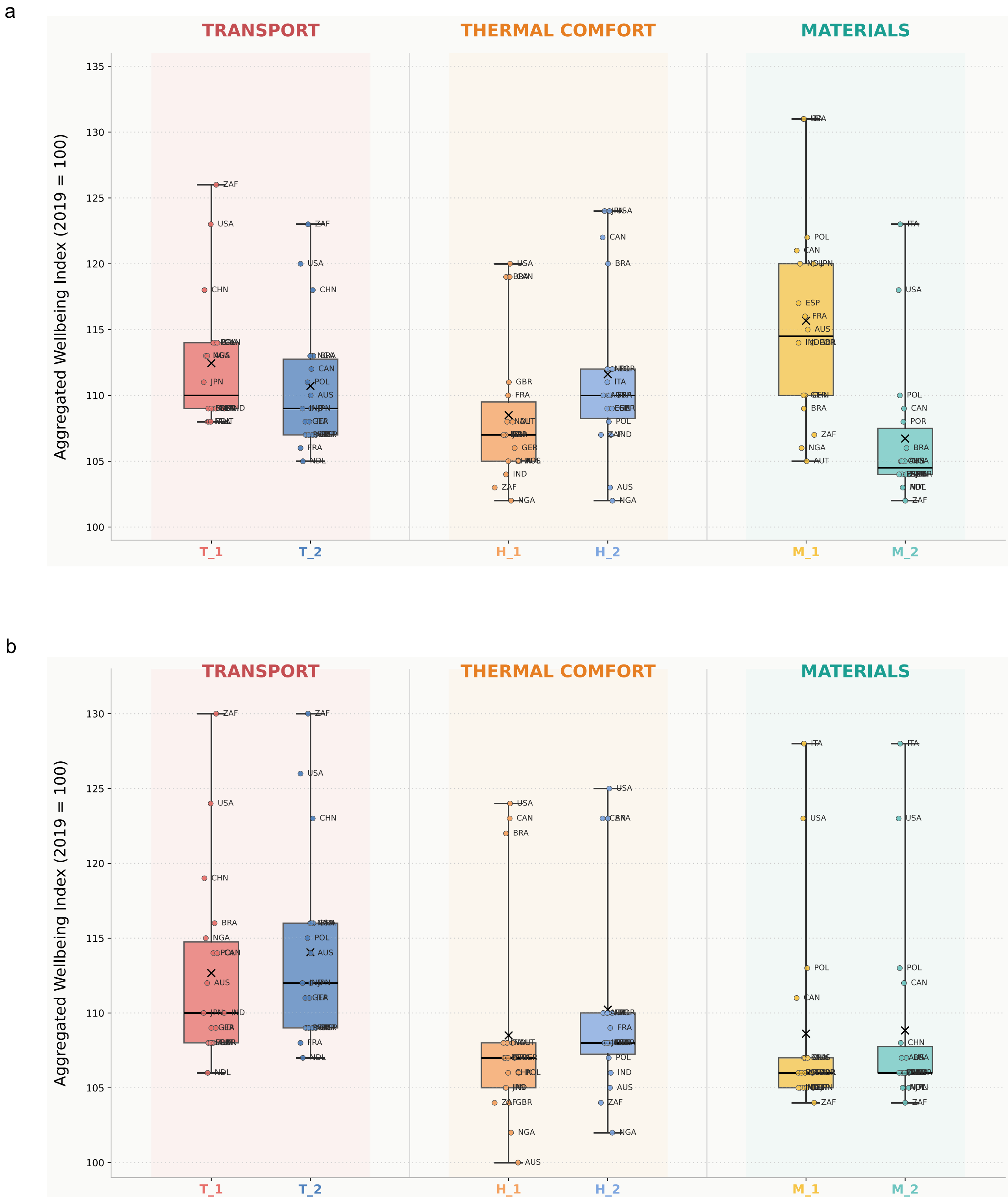


Fig. 2 | Boxplot of aggregate climate mitigation strategy impacts aggregated across the quality-of-life indicators analyzed. Normalized indices with base case 2019 = 100; >100 indices indicate improved quality of life; <100 indices signify declining quality of life compared to the base case. For an explanation of the illustrative six strategies, see Table 1. T transport, H households, M materials; strategies ending with "_1" are the supply-side strategies, and strategies ending with "_2" are the demand-side strategies. The box spans the interquartile range (IQR) from Q1 to Q3, with an internal line for the median and an "x" for the mean; whiskers extend to the most extreme minimum and maximum values. Individual observations are shown as small circles identified with their international country code. Figure 2**a** (top)**:** aggregate of all six quality-of-life indicators. Figure 2**b** (bottom): aggregate of five quality-of-life indicators excluding energy sector jobs.

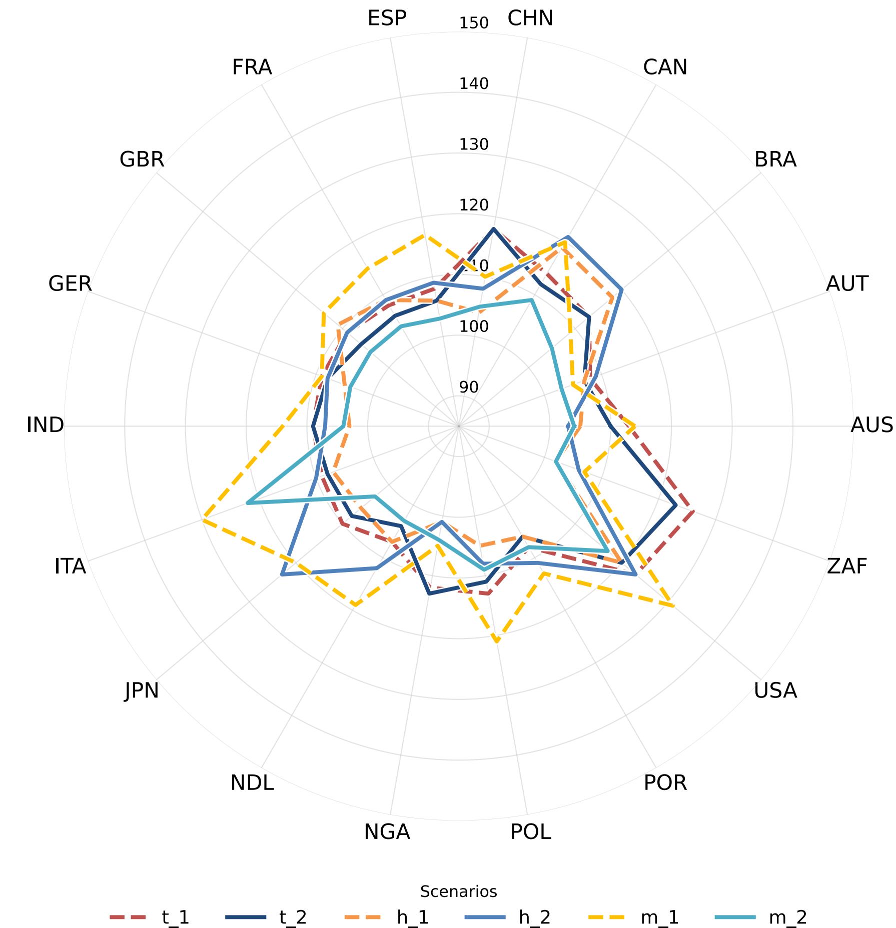


Fig. 3 | Snowflake of aggregate quality-of-life impacts (all 6 indicators) per country across our sample of 18 countries. Normalized indices with base case 2019 = 100; >100 indices indicate improved quality of life; <100 indices signify declining quality of life compared to the base case. For an explanation of the illustrative 6 strategies, see Table 1. t transport, h households, m materials; strategies ending with "_1" (dashed lines) are the supply-side strategies, and strategies ending with "_2" (solid lines) are the demand-side strategies. Detailed country-level results are reported in Tables SM-2-3-1–SM-2-3-12 in the Supplementary Information).

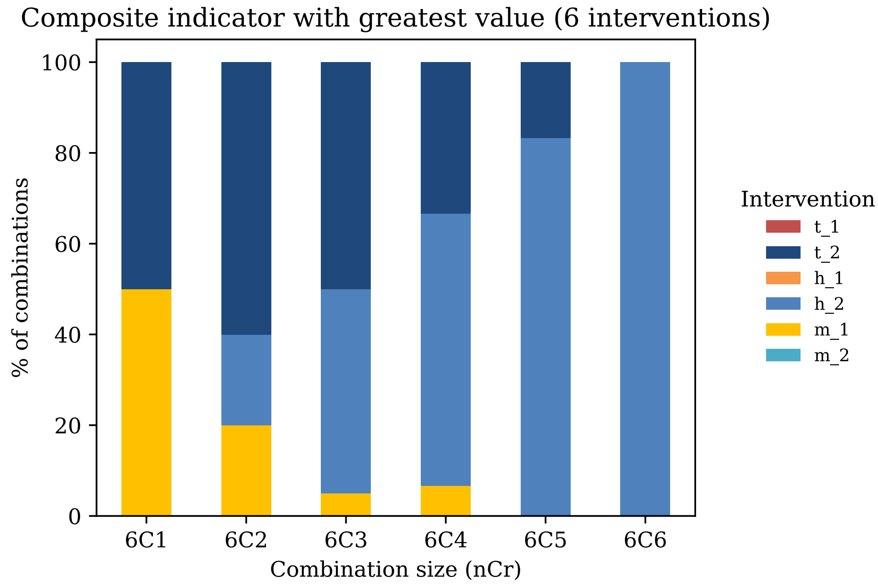
The differences in the importance rankings are comparatively small. When the country-level results (Fig. 5) are introduced as respective weights in the objective QoL assessment, differences to the unweighted mean across all six quality-of-life dimensions (Figs. 1, 2, and 3 above) are small and do not affect the relative ranking of the strategies analysed (see Fig. SM-3-2-4 in Supplementary Information). This is an encouraging result, suggesting that multiple quality-of-life dimensions can and should be considered simultaneously (simply unweighted) in cases where no detailed survey data on their relative importance are available.

Second, people in the three countries generally expect that all six mitigation strategies will positively impact their quality of life (see Fig. SM-3-2-2), and support all strategies (Fig. SM-3-2-3), even though the demand-side strategies assume active engagement and behavior changes, refuting common assumptions that demand-side strategies reduce individuals' quality of life. This is an important finding as experts agree that both supply-side and demand-side strategies need to be implemented to achieve climate goals[4]. Our findings extend recent studies that show that public support for climate policies is stronger than commonly assumed by demonstrating that people generally support demand-side strategies and expect that these will positively impact their quality of life. Third, evaluations of the six mitigation strategies mostly improve after reading objective information about their (mostly positive) quality-of-life impacts (see Figs. SM-3-2-2 and SM-3-2-3). This is a promising finding as people received a very brief description of these objective impacts only once. Fourth, supply-side strategies were mostly (but not always) perceived as having a (slightly) more positive effect on quality of life compared to demand-side strategies, and people were slightly more in favor of implementing supply-side strategies, also after receiving the impact information, even though we found that demand-side strategies have (objectively) more positive quality-of-life impacts than supply-side strategies. Yet, the differences were typically small. Future research is needed to understand the general slight preference for supply-side over demand-side strategies. It may be that people considered other impacts on their quality of life that we did not assess and communicate, such as effort, inconvenience, or autonomy, and just reading information once may not be sufficient to substantially shift individuals' evaluations. Fifth, we found some differences in evaluations across countries, which may be due to differences in physical and social-economic conditions people face.

Limitations

A limitation of our study stems from the national scale applied in this analysis, reflecting the dominant locus of the current climate mitigation architecture (NDCs, Nationally Determined Contributions). The national-level focus implies that impacts at the subnational level or international spillover effects (e.g., employment impacts beyond national borders arising from import of plant, equipment or consumer products) could not be considered but remain on the research agenda. Another limitation of our study is the use of generic, prototypic mitigation strategies as a first important step, leaving the analysis of potential impacts of specific implementation instruments (e.g., subsidies, taxes, regulations) for future follow-up studies. We hypothesize that the overall positive assessment of quality-of-life impacts and acceptability of mitigation strategies found in the surveys could be affected by the choice of the implementation instruments and mechanisms put in place to overcome adoption barriers, such as higher up-front investment costs, which should be tested in future research. Extending the surveys with questions on willingness and intention to implement the mitigation strategies and/or implementation barriers faced are other potential extensions of the research reported here. The methodology and numerical database established in this study can provide a valuable basis for subsequent future research.

Fig. 4 | Combinatorial analysis considering progressively larger sets of quality-of-life indicators, from using only single indicators (C1) to sets of all 6 indicators (C6) for all 18 countries used in the analysis. The bars show the frequency of which a given climate mitigation strategy (denoted by colors) outranks all other strategies under the set of quality-of-life indicators (1–6) considered. t transport, h households, m materials; strategies ending with "_1" are the supply-side strategies, and strategies ending with "_2" are the demand-side strategies. For the definition of strategies, see Table 1.



Conclusions

We now turn to the main conclusions of our study, which we feel are particularly relevant to embrace in national climate mitigation strategies. Our study concluded that policy formulation and implementation could be markedly improved by embracing a wider wellbeing perspective beyond traditional cost-effectiveness paradigms for both assessing the benefits of climate mitigation strategies and for communicating these benefits to the public to increase their acceptability and support. We also demonstrated the importance of considering a wide portfolio approach to climate mitigation, in particular by paying special attention to demand-side strategies that continue to be underrepresented in the policy discourse while generally generating larger and wider wellbeing benefits beyond reduced emissions compared to supply-side mitigation strategies. We also concluded that a framing along multiple well-being benefits not only improves communication but also markedly changes evaluations of quality-of-life impacts and acceptability of climate mitigation strategies by the general public, which is key to the success of any action being considered.

Our study also offers a number of specific conclusions and avenues for future research.

First, mitigating dangerous climate change is typically associated with raising the quality of life. As demonstrated by the six prototypic climate change mitigation strategies examined in this study, all are associated with improvements in quality of life, both objectively and subjectively, although the magnitude of these benefits varies. Notably, demand-side strategies, characterized by reduced consumption, tend to deliver greater objective quality-of-life benefits than conventional supply-side measures. Among supply-side measures, electrification of end-use applications that result in substantial efficiency gains (e.g., electric vehicles relative to internal combustion engine vehicles) demonstrates markedly greater benefits for quality of life compared to fuel-substitution strategies that do not enhance end-use efficiency for the provision of energy services.

Second, although quality-of-life impacts are heterogeneous across the 18 countries analyzed, our results indicate that both high-income and low- to middle-income countries can derive substantial benefits from both supply- and demand-side climate mitigation strategies. This novel finding is particularly relevant for informing international climate negotiations, which are frequently characterized by antagonizing positions between different blocs of countries and misperceptions of negative impacts on the quality of life of climate mitigation. These divergences often stem from conventional economic paradigms that narrowly misconstrue *development* as solely being about increases in gross domestic product (GDP), neglecting broader perspectives of human wellbeing, including health, security, opportunity, and equity. The bias is deepened further because of the narrow focus on the direct financial benefits (e.g., on affordability) that mitigation strategies bring about or not.

Third, while the overall association between climate mitigation strategies and enhanced quality of life is both robust and statistically significant, there remain important nuances. Specifically, trade-offs do exist between employment outcomes (job creation and displacement) and household energy affordability (disposable household net income). While some of the tradeoffs identified result from the system boundaries chosen in the analysis (focus on households and excluding macro-economic feedback and focusing on energy flows and associated expenditures only) and incomplete data available (e.g., employment effects of electric vehicles and their infrastructure, or of material recycling schemes), not all tradeoffs will disappear from a more comprehensive analysis. These trade-offs necessitate the design and implementation of compensatory mechanisms to mitigate against undesirable quality-of-life impacts, an area that requires further analytical and policy attention. Extending the systems boundaries of the analysis beyond the energy sector to assess also non-energy sector or economy-wide impacts for employment and non-energy costs (e.g., for materials and consumer products that may be affected by climate strategies) remains an important future research task for more comprehensive trade-off analyses.

Fourth, people evaluate all dimensions of quality of life as important, even if some differences exist across countries in their specific order, which likely relates to their respective social, economic, and environmental contexts. This implies that policy design should move away from the traditional overemphasis on the economic dimension of climate mitigation strategies and consider a multidimensional perspective on quality of life. In practice, strategy and policy design, policy implementation, as well as ex-post analyses and the overall discourse have to break off with the conventional, almost exclusive focus on cost-effectiveness, to align with a broader quality-of-life approach, which people value highly and that strongly influences evaluations and acceptability of different mitigation strategies.

Fifth, providing objective estimates of the quality-of-life impacts of mitigation strategies increases people's positive expectations of and support for both supply- and demand-side mitigation strategies across different sectors markedly. We found that people generally evaluate all mitigation strategies positively (i.e., they expect positive impacts on quality of life, and find the strategies acceptable), but supply-side options are slightly favored despite somewhat lower objective benefits. Possibly, people considered other quality-of-life impacts that we did not assess in our study, such as implications for autonomy, effort, or inconvenience. People also may not have fully grasped the different quality-of-life impacts of demand-versus supply-side strategies, as in the randomized pair-wise survey protocol, they were asked to evaluate strategies one after the other and could thus not

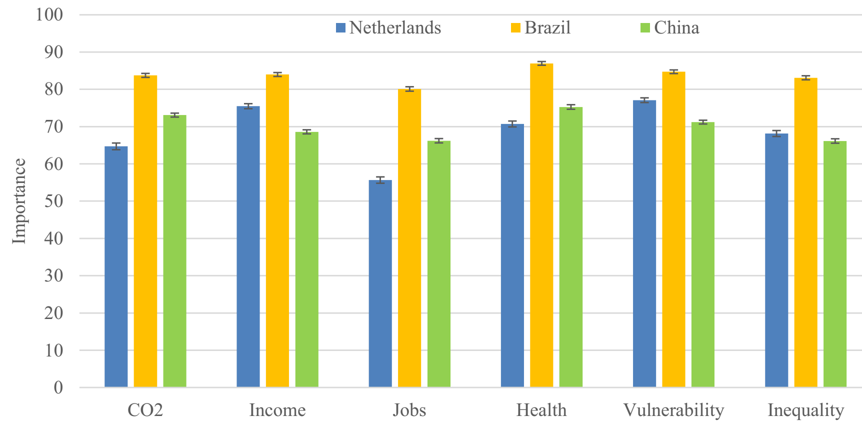


Fig. 5 | Evaluation of the importance of six quality-of-life dimensions in empirical surveys. Based on survey data in the Netherlands ($N = 824$), blue bars; Brazil ($N = 1298$), yellow bars; and China ($N = 1400$), green bars; mean of country samples, and error bars (±one standard deviation).

directly compare their quality-of-life impacts. Or simply a few minutes of exposure to information was not sufficient to shift perceptions more than marginally; longer or deliberative formats may be required to substantially shift evaluation of demand- and supply-side strategies. Notably, we did not find support for the often-postulated aversion of the public against demand-side strategies. People evaluate demand-side strategies positively, even if there is a tendency to evaluate supply-side strategies even more positively. Hence, more work on both quantifying quality-of-life impacts and for continued tailored communication efforts on mitigation strategies is called for. International assessments, such as within the IPCC, are a good place to start such efforts. Quality-of-life-focused communications about climate mitigation strategies could be a worthwhile avenue to explore further to depolarize the debate and to build a broad support base by activating core values and demonstrating the shared values among different groups of people.

In summary, all climate change mitigation strategies analyzed improve quality of life with wide benefits beyond lessened climate impacts. Demand-side strategies tend to offer greater benefits for the overall quality of life than supply-side strategies. However, these benefits are not yet always fully recognized by consumers and policymakers. Importantly, our study finds that when individuals are informed of the objectively assessed quality-of-life impacts of different mitigation strategies, their subjective perceptions can become more positive. This suggests that greater transparency and communication around quality-of-life benefits beyond climate could play a pivotal role in increasing public and political support for ambitious climate action.

By combining a broad comparative assessment of macro-level and micro-level quality-of-life impacts across multiple mitigation strategies and countries, this study provides a foundational contribution to understanding climate action through a wellbeing lens.

Methods

Quality of life as a focal element

Quality of life is influenced by a range of factors (see Table SM-1-1 in Supplementary Information), many of which are particularly relevant in the context of climate mitigation strategies. To meaningfully assess the implications of such strategies, it is essential to differentiate between how demand-side and supply-side strategies affect various dimensions of quality of life. This requires identifying the dimensions that are most suitable for policy evaluation. Since we use models to analyze multiple demand- and supply-side strategies across different national contexts in this work, we also need to establish to what extent the quality-of-life dimensions represented in models correspond to those that individuals actually perceive as relevant to their lives.

Our goal in this work is to assess the short-term (approximately 10-year) quality-of-life impacts of demand-side vs. supply-side climate mitigation strategies, through both objective and subjective lenses. Objective assessments refer to quality-of-life indicators at the aggregate macro level (country, income groups), whereas subjective assessments look at the micro-level to capture individuals' own evaluations of how such strategies are expected to influence their quality of life. By integrating these distinct approaches, our study offers a more comprehensive and robust understanding of the extent to which climate mitigation strategies affect quality of life for individuals and societies.

At the macro level, we perform simulation-based analysis of objective societal or national-scale impacts using six quality-of-life dimensions that have been identified in previous literature as potentially important benefits of climate mitigation: (1) household disposable net income (net of energy costs) [$]; (2) jobs in the energy sector [#]; (3) CO_2 emissions reduction [index, base = 100]; (4) energy supply vulnerability reduction [index]; (5) health benefits from $PM_{2.5}$-related mortality reduction [avoided deaths]; and (6) energy inequality reduction [index, change in energy cost difference between the lowest income quintile and the country average]. The limited set of indicators analyzed here reflects both the principle of scientific parsimony and the specific research questions in our study. The results from the empirical survey demonstrate that all six dimensions and indicators were considered of high importance by survey respondents.

We complement the macro analysis with empirical surveys that capture subjective perceptions of quality-of-life impacts at the micro level. This aspect of the study constitutes a novel contribution, given evidence that subjective perceptions of how climate mitigation strategies affect individual quality of life are critical determinants of ex-ante public acceptability[17,18]. Survey participants are asked (1) to what extent they consider the six dimensions of quality of life (see above) important; (2) how they expect a particular climate mitigation strategy to affect their individual quality of life, and to what extent they find each strategy acceptable; and (3) how their perception of a strategy's perceived quality-of-life impacts and acceptability changes when they are presented information about the strategy's objectively analyzed impacts on quality of life.

This dual-level, mixed-methods approach enables a nuanced understanding of how climate mitigation strategies are evaluated by different individuals, how these evaluations change after receiving objective information on quality-of-life impacts, and how these perceptions align—or diverge—from objective assessments.

Objective-macro simulation analysis

Our objective macro simulation analysis aims to objectively assess the impact of different supply- and demand-side strategies on six dimensions of quality of life: economic subsistence (disposable income), jobs, health, security, equity, and climate. We use six quantifiable quality-of-life indicators as well as several indicator-subvariants for each indicator (see Supplementary Note SN-2-2).

Quality-of-life indicators and their strategy-induced changes are model-derived estimates determined on the basis of physical energy flows (e.g., electricity production/use, imports and exports, coal or oil products used) multiplied by corresponding coefficients, such as emissions factors

(CO_2 and $PM_{2.5}$), labor market multipliers per unit energy supplied (or conserved in the case of building insulation), as well as direct energy (fuel) costs, compared to disposable household income statistics. For the indicators, we use available authoritative national-level statistics (e.g., IEA energy balances[19], and energy prices statistics, and the OECD Better Life Index statistics[20]), the latest available literature[21] for $PM_{2.5}$ air pollution and health impacts, as well as meta-studies integrating a large body of empirical estimates, as in the case of the employment effects of energy supply provision and end-use conservation per unit of energy. Indicators, their statistical data sources, and references are documented in Table SM-2-2-1 in Supplementary Information.

We first represent countries' energy systems and their associated emissions, costs, and quality-of-life indicators for a common base year (chosen as 2019). Then, for a range of prototypic climate mitigation strategies, we adopt an illustrative target of a -10% CO_2 emission reduction compared to the base year. This approach allows for a before-after comparison without the need to consider inter-temporal transition aspects.

For each of the climate mitigation strategies analyzed, the simulation tool determines all relevant up- and downstream changes in energy flows (e.g., the mitigation strategy of thermal retrofit of buildings via improved insulation yields a reduction in useful energy flows of the dominant domestic heating sources (understood as energy services here), which then instigates corresponding changes in final energy that is purchased by households, and also generates upstream changes in apparent primary energy consumption (domestic production plus net imports), see Supplementary Note SN-2-1). These changes in energy flows affect the various quality-of-life indicators to differing degrees. Thus, each climate strategy analyzed results in a somewhat reconfigured energy system for each country, all the way from primary energy down to the level of useful energy delivering energy services.

To simplify analyses and, above all, ease an intuitive, simple communication of results in the subsequent empirical survey, we have adopted a simple taxonomy to select our illustrative mitigation strategies aiming to reduce CO_2 emissions by -10%. We first consider three sectors representing the major energy end-uses: buildings, transport, and materials (industry). We then consider, for each sector, a prototypic supply-side strategy (i.e., fossil fuel substitution) versus a prototypic demand-side strategy (i.e., improved energy efficiency and conservation). In each pair of strategies for each sector, the resulting change is always -10% CO_2 emissions. The six illustrative, prototypic strategies deemed to be implementable within a decade are summarized in Table 1 above. Note that in all cases of fossil fuel substitution via electrification, additional electricity demand is assumed to be provided by zero-carbon domestic renewables (solar and wind). Note also that the focus of our analysis is on generic strategies and not on particular policy instruments (such as regulations, subsidies or pricing measures) that may be used in the subsequent implementation of a strategy, once the wider QoL benefits and acceptability of the strategies have been established, which is the objective of this study.

The analysis was performed for a sample of 18 countries (see SN-2-2), representative of the diverse national circumstances that may affect the quality-of-life impacts of climate mitigation strategies. The countries hail from the Global North and Global South and include both energy importers and exporters, and both large and small economies. In aggregate, these 18 countries account for 25 Gt of CO_2 emissions, or almost 75 percent of global energy-related CO_2 emissions in 2019 (34 Gt, cf. IEA[22]). The choice of the countries analyzed was determined by the availability of disaggregated energy statistics, especially at the end-use (useful energy) level, as well as the desire to maintain comparability to an earlier study on macro-level energy security by the authors that applied a similar methodology[23].

Subjective-micro survey analysis

We additionally conducted surveys among representative samples in three of the countries that were included in the simulation study: Brazil ($N = 1298$), China ($N = 1400$), and the Netherlands ($N = 824$); see Supplementary Note SN-3-1 for a detailed description of the surveys. (Resource limitations did not allow to conduct surveys in more countries.) The surveys aimed to examine: (1) how important respondents find each of the six quality-of-life dimensions when evaluating mitigation strategies (Fig. SM-3-2-1 in Supplementary Information); (2) how people expect the demand- and supply-side strategies will impact their quality of life and how much people support these strategies; and (3) whether communicating the objective quality-of-life impacts changes perceived quality-of-life impacts of and support for the six strategies (Figs. SM-3-2-2 and SM-3-2-3). The strategies surveyed were described using simplified narratives and visual summaries (see Supplementary Information pp. 21–31) to adequately communicate these to nonexperts. We conducted a pilot study prior to implementation of the survey to verify that respondents could understand the strategies and the quality-of-life dimensions considered and adapt the questions and descriptions accordingly.

Data availability

All data presented in this paper are documented in the Supplementary Information. Numerical data underlying the graphics and the tables (article and Supplementary Information) are also archived in a data repository: https://doi.org/10.5281/zenodo.20269925.

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Author contributions
Arnulf Grubler and Linda Steg co-designed the study and co-supervised the project. Grubler, in addition, contributed to the country analysis, drafted the text and handled the manuscript submission. Steg co-designed the empirical surveys and contributed to their analysis and to the drafting of the manuscript text. Nuno Bento developed the national-level energy simulation tool and objective quality-of-life impact analysis, contributed to the country analysis and to the drafting of the manuscript text and Supplementary Information material. Benigna Boza-Kiss contributed to the country analysis, editing of the manuscript text, the development of material for the Supplementary Information, to the drafting and editing of the manuscript text and handled the reference management throughout the project. Simon De Stercke contributed to the country analysis and the development of material for the Supplementary Information. David McCollum contributed to the country analysis and the drafting and editing of the manuscript text. Sascha Nick co-developed the quality-of-life framing of the study and contributed to the drafting of the manuscript text. Shonali Pachauri contributed to the cross-national country analysis and to the drafting and editing of the manuscript text. Anne van Valkengoed co-designed the empirical country surveys, contributed to their implementation and analysis and to the drafting of the manuscript text. Caroline Zimm contributed to the country analysis and to drafting the manuscript text. Tiago Louro Alves performed the uncertainty and sensitivity analysis of the national level quality of life impacts. Chao Qin co-designed and implemented the empirical country surveys, analyzed the results, and prepared material and text for the Supplementary Information. All authors have read and commented on the draft manuscript, the study results, and their documentation.

Competing interests
The authors declare no competing interests.

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