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# Preferences of young people reshape modeled national energy system designs toward offshore wind

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Muhammad Shahzad Javed [1] ✉, Karin Fossheim[2], Maximilian Roithner[1], Matylda N. Guzik[1], James Price[3], Beate Seibt [2] & Marianne Zeyringer[1]

Visual impact and unequal cost-benefit distribution pose barriers to the acceptance of renewable energy needed to meet climate targets. Achieving sustainable energy transitions requires understanding how societal groups navigate environmental, economic, and equity trade-offs. Here, we develop a participatory energy system modeling framework that incorporates participants across the modeling process, systematically integrates their preferences, and enables iterative learning through feedback sessions. We find that Norwegian high school student preferences, particularly strong opposition to onshore wind in valued landscapes and specific regions, reduce land-based capacity potential by half, result in offshore wind entirely substituting onshore, and raise system costs by up to 25%. These costly youth-driven systems are not necessarily more equitable. Feedback sessions reveal that exposure to trade-offs encouraged preference reconsideration and fostered deeper understanding of transition challenges. This study supports structured reflection on system trade-offs and provides a replicable methodology for systematically integrating stakeholder perspectives into technically rigorous energy planning.

There is a growing consensus on the necessity of interdisciplinary approaches for analyzing and designing future energy systems. One area where this requirement manifests is in siting decisions for new variable renewable energy (VRE), often perceived as posing social and environmental risks and injustices[1]. In particular, the visual impact, changes in landscape esthetics and environment, and unequal distribution of costs and benefits pose considerable barriers to the acceptance of new VRE deployments[2,3]. These concerns can erode trust in public institutions and democratic processes, prompting governments to retract or reconsider proposed VRE developments[4–6]. One example is the abandonment of the Norwegian Water Resources and Energy Directorate (NVE) national framework proposal, which intended to pinpoint viable areas for onshore wind development spanning 29,000 km$^2$ (9% of total land area), with an estimated capacity of ~290 GW, due to public criticism[7]. In response, governments increasingly decentralize the VRE planning process to ensure projects offer socio-economic benefits to all community groups[8,9].

Since 2019, underrepresented groups, particularly young people, have increasingly voiced concerns on energy and climate issues through climate strikes, protests, and legal actions[10], advocating for meaningful measures through filing climate justice cases and a more inclusive energy transition process[11]. For example, Norway-based youth-led groups promote nature preservation and have been opposing certain wind power installations for this reason[12,13]. Monetary considerations cannot fully address the concerns and values young people hold regarding the energy transition[14]. Studies indicate young individuals promote environmental literacy and are eager to contribute to the energy transformation[15]. Despite growing evidence of climate-related psychological distress among youth worldwide[16], there remains a lack of large-scale, meaningful engagement with them. Thus, empowering youth can help address the overlooked concerns of marginalized groups in the energy transition, thereby enhancing social acceptance through their forward-looking stance, willingness to engage with new information[17], and involvement in internet-based social movements[18].

Energy system modeling (ESM) is an essential tool to study the design of future energy systems that meet commitments under the Paris Agreement. Their techno-economic nature provides insights into challenges, transition pathways, and sensitivity to technological and policy developments. Despite their role in supporting decision-makers, quantitative ESMs often fail to sufficiently integrate stakeholder perspectives necessary to adequately address the energy transformation's social dimension alongside techno-economic details[19]. Participatory approaches in ESM enable the design of scenarios by generating bottom-up knowledge of stakeholder perspectives regarding energy transition[20,21]. Participatory ESM have used

[1]Department of Technology Systems, University of Oslo, Oslo, Norway. [2]Department of Psychology, University of Oslo, Oslo, Norway. [3]UCL Energy Institute, University College London, London, UK. ✉e-mail: m.s.javed@its.uio.no; shahzad.sjtu@yahoo.com

approaches like online surveys[22], factsheets[23], group discussions and interviews[24], multi-criteria decision making[25], and interactive tools[26–28]. However, public engagement needs to extend beyond assessing whether people accept or reject proposed technologies to active co-production of energy futures[29]. Studies demonstrate participants' capacity to navigate complex trade-offs when provided appropriate information and deliberative space[30,31]. Whilst there is a growing body of literature (see Supplementary Table 1) engaging people in energy system planning, limitations in the representation of specific demographics and engagement depth persist[32].

Although approaches like interactive tools facilitate learning about energy system planning by exploring various combinations of system components, they often fail to support collective learning. This limits their ability to address knowledge gaps about renewable electricity technologies and provide context for informed energy choices, potentially leading to misconceptions about impacts[3,20]. Moreover, explicit stakeholders' perspectives on power system components, particularly regarding acceptance and equity, remain relatively unexplored[33]. For example, participants might choose onshore wind under conditions that exclude certain landscapes and ensure regional equity. Furthermore, the majority of participants in previous studies consist of various experts, with the general public comprising fewer than 20% of available studies, indicating certain groups, especially young people—with the exception of study[26]—are overlooked[20,33–35]. Consequently, a framework that meaningfully incorporates particular stakeholder groups across the ESM process—including scenario design, optimization, results discussions, and feedback—remains lacking[34–37].

One way to address this is through educational workshops during school hours, which may act as a building block for fostering mutual understanding between young people, local stakeholders, and national planners. Such initiatives, developed as intervention tools, can enable young people to form and express opinions about the energy transformation process. We conduct full-day compulsory workshops (three 90-minute sessions) in five schools, involving 286 students aged 15-16 from diverse backgrounds. Through interactive activities and games during these sessions, we discuss the basics of the green energy transformation, potential conflicts related to VRE installations, and climate justice. These workshops facilitate collective learning and provide context for informed energy choices, aligning with our aim of empowering and meaningfully engaging young people in the energy system planning. We design questionnaires to collect students' perspectives on key aspects of the power system. This study contributes to participatory ESM in three ways. First, it provides a framework for incorporating stakeholders' perspectives across the ESM process—scenario design, results discussion, and feedback—moving beyond approaches that engage participants in isolated components. Second, it systematically integrates stakeholders' techno-economic and environmental preferences into the ESM through modeling equations rather than treating them as pre- or post-modeling qualitative discussions. Third, it implements iterative engagement through formal feedback sessions in which participants deliberate on the modeled implications of their preferences. This replicable approach will enable modelers to integrate diverse stakeholder perspectives while maintaining technical rigor.

This study focuses on Norway's electricity system for variable renewable electricity generation, including onshore wind, bottom-fixed offshore wind, floating offshore wind, and solar photovoltaics, while ensuring an adequate net-zero power system for 2050. We modify a spatiotemporally detailed electricity system planning model[38], incorporating various settings based on students' preferences: technology choices, regional preferences for VRE siting, self-sufficiency (defined as annual electricity imports equal to annual exports), choices for new power lines buildout, and the exclusion of certain landscapes. (see Methods, Supplementary Note 2, Supplementary Table 6). Although systematically integrating stakeholder perspectives may result in higher electricity system costs, modeled scenarios may perform better on non-modeled objectives, such as political feasibility, social acceptance, and energy justice[39,40]. This aligns the ESM more closely with real-world considerations and political discourse.

## Results

We use an open-source capacity expansion model, highRES[38], that optimizes spatial allocation of new VRE installations alongside operational decisions, transmission infrastructure, and energy storage while minimizing total system costs (capital and operating). The model operates as a hybrid greenfield approach under a strict emissions constraint (0 $gCO_2$-kWh)[41], excluding existing solar- or wind-based installed infrastructure while treating hydropower capacity and existing transmission as fixed. The Norwegian electricity system is optimized for 2050 electricity demand[42]. Student preferences are integrated as binding constraints that restrict the solution space, while the model continues to optimize for minimum system cost within these boundaries. For instance, landscape preferences exclude grid cells containing opposed landscape types from the available deployment area; technology preferences set upper bounds on capacity shares; and regional preferences cap technology deployment per county (See Methods).

The scenarios based on students' input capture power system aspects that constitute most of the system cost and encompass land use conflicts and visual impacts; factors that challenge social acceptance[33]. The base model includes only the core technical, environmental, and geographical restrictions[42] and does not incorporate students' preferences. The transmission (trans) scenario reflects students' choices about maintaining or expanding current power lines, using visible overhead lines or expensive underground lines. The trade scenario represents inclinations regarding electricity trade levels with neighboring countries, with options to decrease, increase, or maintain current import levels. The technology (tech) scenario reflects students' selection of VRE (wind and/or solar) through discrete choice experiment questions. Students were not asked to distinguish between bottom-fixed and floating offshore wind during workshops, as this technical distinction proved too complex for the age group[43]. The landscape (land) scenario integrates preferences for nine common Norwegian landscape types for onshore wind development based on national map data[44]. The region scenario indicates students' spatial choices for siting new VRE across Norwegian counties. We derived preference coefficients from a detailed assessment of workshop responses and integrated them into the modified energy system model.

We assess the impact of individual, cumulative, and different prioritization sequences of student choices on the future design of net-zero electricity systems. Figure 1 illustrates the framework workflow. A follow-up feedback session encouraged students to reflect on the outcomes of their energy choices by discussing how their preferences influence the design of a future net-zero electricity system. The modeling output thus enabled a meaningful and fact-based dialog between students on possible future electricity system designs. Complete methodological details of workshops, scenarios, and energy system model modifications are described in the Methods.

### Impact of excluded landscapes on national capacity potential

Given that debates over VRE deployment often center on environmental and landscape impacts, we find that students' preferences as to which landscapes they would include or exclude from VRE deployment affect Norway's renewable potential in different ways. Figure 2a represents the proportion of land available for VRE relative to each county's total area after the exclusion of landscape types students opposed—primarily agricultural, residential, and forested areas. These landscapes are predominantly located in Southern and Eastern Norway, where 57% of the population resides. Although accounting for 42% of electricity demand, landscape preferences there lead to a 72% reduction in generation capacity potential, decreasing the country's onshore wind capacity potential from 371 to 180 GW (Fig. 2b). While selected wind sites align with students' societal and environmental priorities, their distance from demand centers and infrastructure (Supplementary Fig. 15) may necessitate expanding energy storage or transmission capacities. This introduces logistical (i.e., constructing and maintaining the grid in difficult and remote terrain) and possible acceptance challenges associated with transmission lines, and incurs extra storage costs.

The more than twofold reduction in Norway's land-based wind capacity potential becomes concerning, given the projected rise in electricity

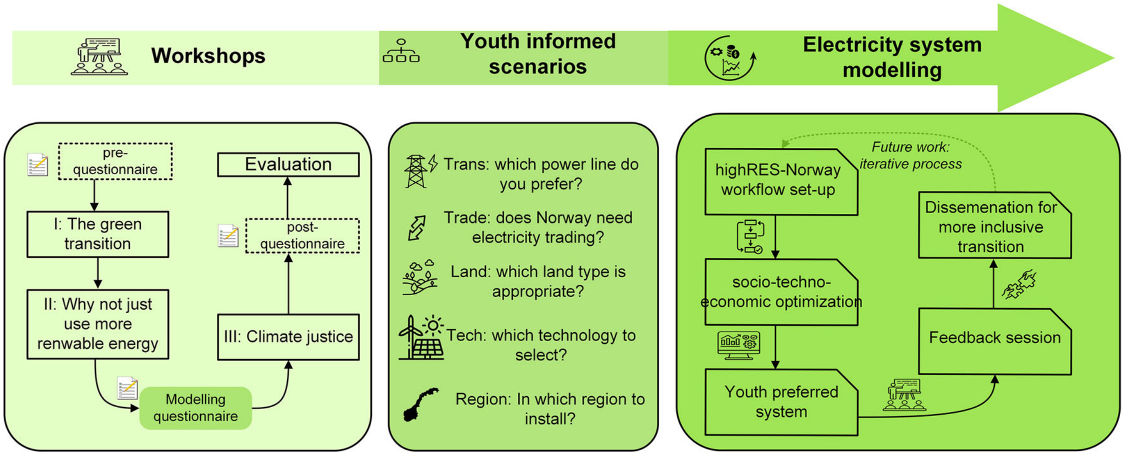


**Fig. 1 | Workshop-based participatory energy system modeling framework.** School workshop-informed multidisciplinary workflow for inclusive power system modeling to develop more socially acceptable energy transition pathways. Workshops consisted of three sessions discussing the basics of green transition, potential conflicts of only building more VRE, and climate justice. The depicted questions are rephrased from the modeling questionnaire used to capture students' perspectives on various aspects of the power system. Exact wording can be found in the workshop materials [credit: energy system icons, Iconjam, www.flaticon.com].

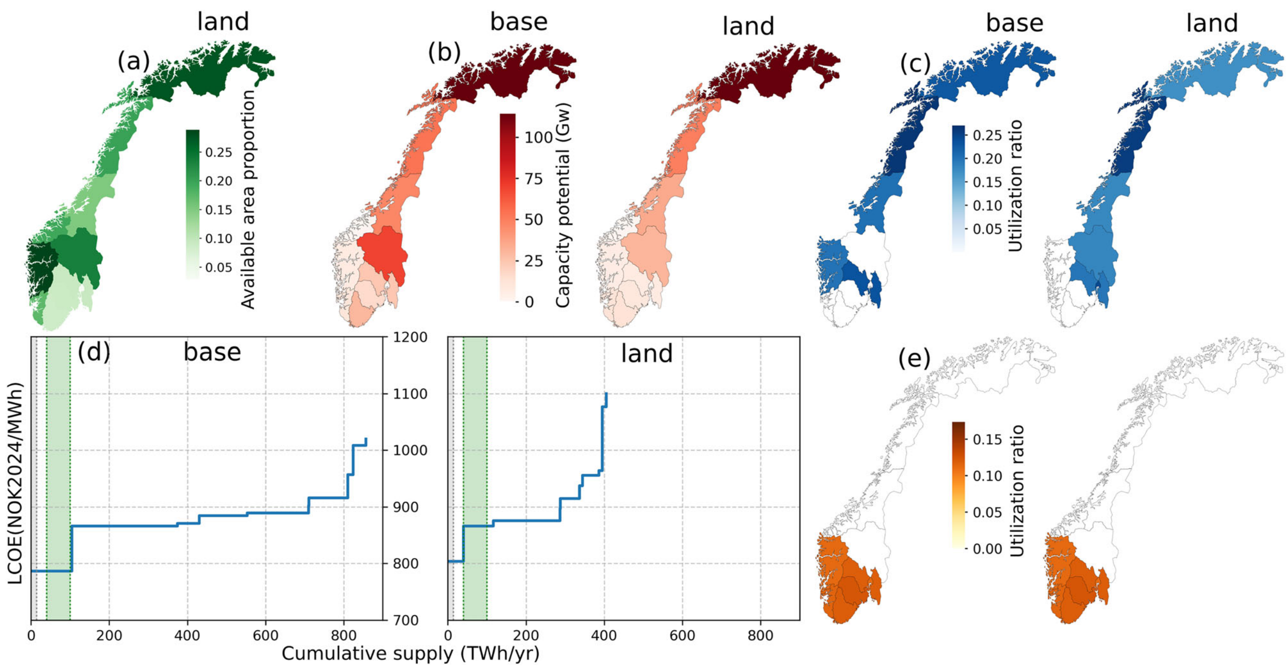


**Fig. 2 | Impact of landscape choices on onshore wind capacity potential.** **a** Proportion of zonal area available after excluding opposed landscapes; **b** Comparison of the countrys' onshore wind capacity potential before (base) and after (land) excluding opposed landscapes. Available areas are aggregated into zones (Norways' administrative regions) and subsequently converted to capacity potential; **c** Utilization ratio of onshore wind (actual generation divided by theoretical generation) before and after the landscape exclusions; **d** Cost-potential and supply curve for land-based wind installations, with each step corresponding to a zone. The gray line represents the wind power generation in Norway in 2024, while the light green area represents the projected additional electricity demand by 2050; **e** Utilization ratio of solar before and after landscape exclusions, illustrating minimal change. See Supplementary Fig. 1 for solar capacity potentials and Supplementary Fig. 15 for zone descriptions.

demand by 2050[45]—highlighted by the green areas in Fig. 2d—combined with an estimated 10% increase in the levelized cost of electricity (LCOE), which underscores the economic impact of the landscape preferences. Summarizing, the decreased available area for VRE leads to higher system costs due to: i) deploying capacity in suboptimal locations that are either less windy or distant from demand centers, requiring transmission expansion; ii) potential total capacity limits on onshore wind due to socio-economic restrictions limiting its national-scale contribution to decarbonization; and iii) increased reliance on more expensive alternatives, such as fixed and floating offshore wind (with their own future transmission implications) alongside greater storage and flexibility requirements. While excluding unfavoured landscapes marginally reduces the country's mean onshore wind capacity factor by 3.1%, the utilization ratio (actual generation divided by theoretical generation) decreases on average by 13.78%, reflecting system-level bottlenecks of integrating landscape preferences (Fig. 2c). In contrast, the solar utilization ratio decreases minimally by 0.84%, indicating its adaptability from both technical and social perspectives (Fig. 2e).

### Students' expectations change technology compositions and system costs

Figure 3 shows the national installed VRE capacities for net-zero 2050 electricity systems, excluding hydropower. Deviations from the baseline

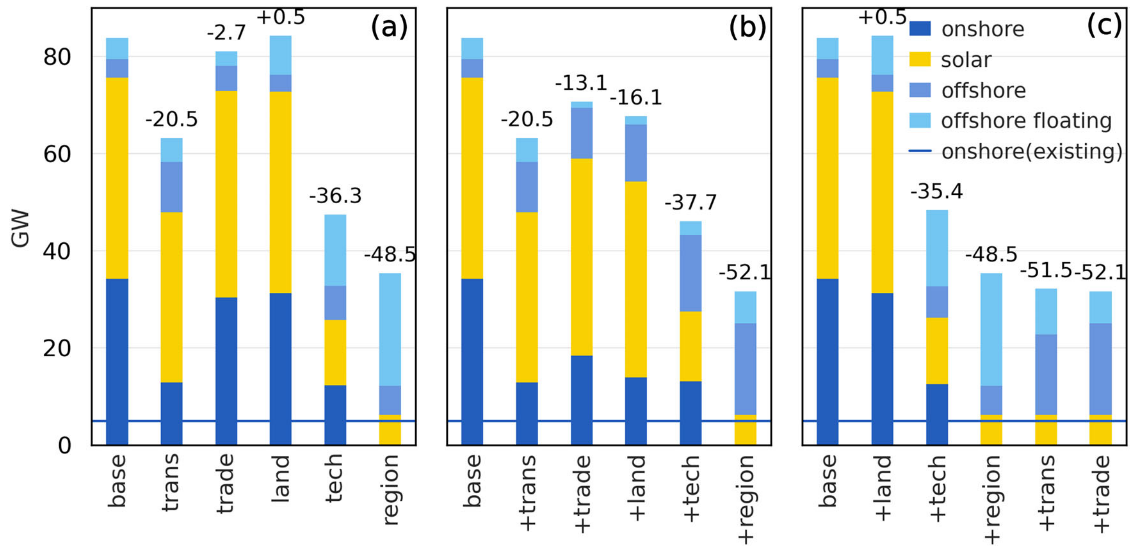


**Fig. 3 | National installed capacities for a 2050 net-zero electricity system.** **a** Demonstrates the impact of each scenario individually, while **b** and **c** depict the cumulative capacities as student preferences are sequentially and incrementally added in a specified order. For context, the blue line indicates the current installed capacity of onshore wind in Norway. Reductions in onshore wind capacity are largely substituted by offshore wind.

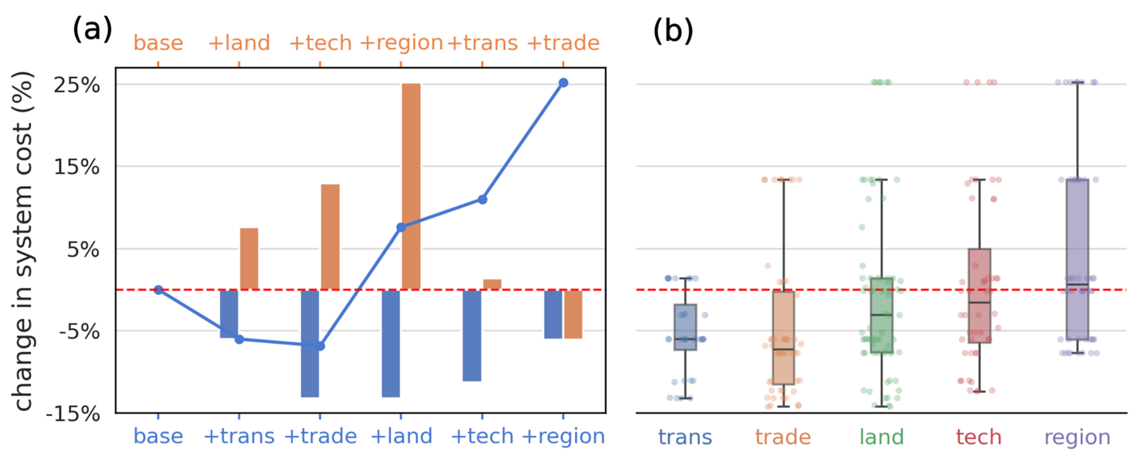


**Fig. 4 | System costs for a 2050 net-zero electricity system. a** Change in the system costs from the base scenario. The blue line indicates the impact of the individual scenarios, while the bars depict the cumulative effects of scenarios applied in the specified contrasting order. The blue color refers to the bottom x-axis, whereas the brown color corresponds to the upper x-axis. See Supplementary Fig. 7 for changes in system costs for the 2030 and 2040 demand years. **b** Sensitivity of system cost when the highest priority is assigned to a specified scenario, with other choices incrementally added following all possible sequencing orders (Supplementary Table 5). Box plots show the interquartile range and median, with whiskers extending to 1.5 times the interquartile range. The dotted red line denotes the base scenario. System cost compositions are in Supplementary Figs. 11–12.

scenario reduce total new VRE capacity, except when landscape preferences are incorporated, which increases total capacity. This is because the model invests more in offshore wind, which has higher capacity factors and thus requires less capacity. Young people's choices substantially reduce the share of onshore wind capacity, from ~40% (base) to 0% under stringent regional considerations. This is largely replaced by offshore wind, increasing its share from 9% to as much as 82% in the net-zero 2050 electricity system. Regional choices are most restrictive, reflecting students' decisions on what, where, and how much VRE to install at the zonal level (see Methods). Although converging to similar total capacities, Fig. 3b, c illustrate the most contrasting outcomes across various prioritization sequences of the student's choices. They showcase a quantification of the incremental implications of prioritizing certain aspects of the power system for a more inclusive energy transition. Although hydropower dominates Norway's electricity system (>85%), the results indicate that additional energy storage will be needed by 2050, with capacity fluctuating between 70 and 125 GWh depending on the choices made (see Supplementary Figs. 4–6 and related discussion).

Several key insights emerge: Firstly, irrespective of socioeconomic preferences, the order, or the higher costs associated with offshore floating wind, it is anticipated to contribute to the future electricity system, ranging from 5 to 70%, owing to favorable wind conditions along the Norwegian coast and deep water. Secondly, the deployment of onshore wind is sensitive to local acceptance and regional perspectives. Lastly, a consistent solar deployment (20–50%) is evident despite Norway's limited annual sunlight, indicating the utilization of higher-capacity factor regions near demand centers, such as the South and East of Norway. Similar trends are observed across 2030 and 2040 demand years (Supplementary Figs. 2–3).

Transmission and trading preferences reduce the system cost by 6–7% (blue line in Fig. 4a), attributable to substantial transmission infrastructure investments that enable the deployment of renewables in more cost-effective locations for the system. Although annual electricity import and export levels are matched to reflect students' desire for self-sufficiency, increased dispatch flexibility helps lower costs. Total network capacity increases from 55 to 96 GW, facilitating connections for new offshore installations from the

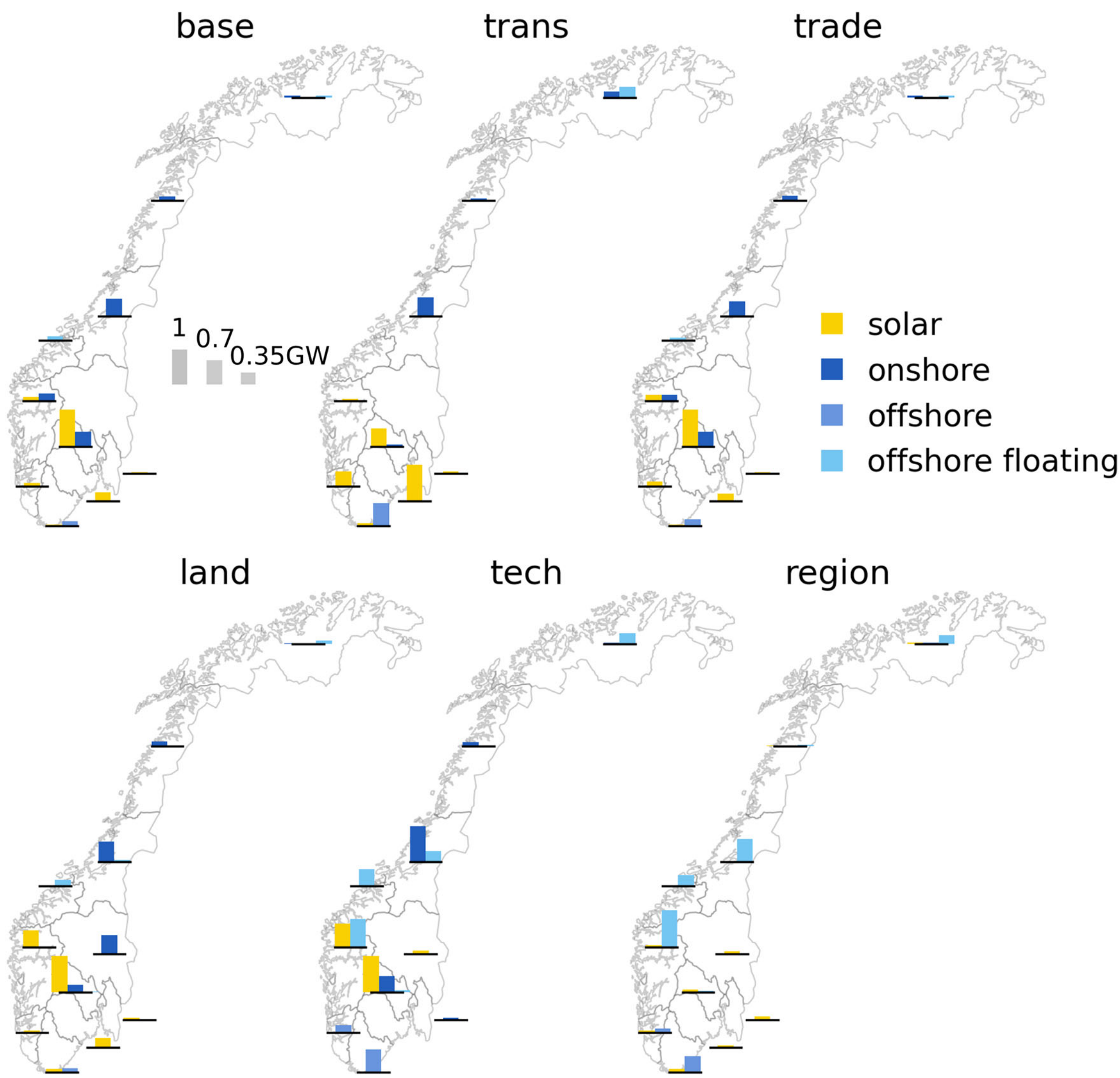


**Fig. 5 | Spatial allocation of installed capacities across zones.** Capacities are normalized to the maximum capacity across technologies within the given scenario, facilitating a comparative assessment of capacities across zones. Supplementary Fig. 13 illustrates the current spatial allocation of transmission capacities and new additions respecting student choices.

north and west to eastern and southern located demand centers (Fig. 5, Supplementary Fig. 13.). Conversely, prioritizing landscape, technology, and regional choices increases system costs by up to ~25%; however, these costs can be offset through transmission and trade choices even under the most stringent regional priorities (Fig. 4a, brown bars). Figure 4b indicates that, except in the most constrained region scenario, the median cost of the 2050 net-zero system is generally lower than the baseline, regardless of the prioritization or strictness levels reflected in students' choices. This outcome results from the flexibility enabled by transmission expansion and increased cross-border electricity trade. The transmission and trade sensitivity analysis further confirms these median system cost reductions (Supplementary Figs. 8–10).

### Regional equity and priorities

While Fig. 3 depicts the influence of young people's choices on the national VRE capacity mix, the VRE's spatial allocation offers further insights into the impact of socioeconomic preferences on the system equity. Spatial patterns of transmission and trade preferences exhibit a more uniform distribution of solar capacities in eastern and southern Norway than baseline (Fig. 5). Interestingly, certain western (Møre og Romsdal, Vestland, and Rogaland) and eastern (Innlandet) zones exhibit only negligible new capacities, despite having substantial available land for VRE installations and high electricity demand (Fig. 2a, Supplementary Fig. 15). The Norwegian government's objective to develop the majority of offshore wind farms along the western coast is primarily realized under regional priorities and technological choices. These new offshore wind installations leverage existing hydropower capacities in the west and interconnections with Germany, the Netherlands, and the UK. Although onshore wind is entirely phased out under regional preferences, unlike in other scenarios, solar installations are modestly distributed across eastern and southern zones, where higher building density and solar potential make them well-suited for both rooftop and ground-mounted installations while adhering to preferences.

The obtained student-based system configurations allow us to evaluate variations in distributional equity across zones using the widely adopted statistical indicator, the Gini coefficient. Since distributional justice can be defined in multiple ways, we examine the distribution of electricity infrastructure across zones relative to electricity demand, total land area, and population[41] (see methods). Across the considered distributional justice framings, the trans scenario generally emerges as the most inequitable one, while the land scenario is the most equitable, followed by the tech scenario (Fig. 6). The total system cost variation between the least and most inequitable scenarios is ~15%, suggesting that more equitable solutions come with moderate additional costs that must be weighed against the

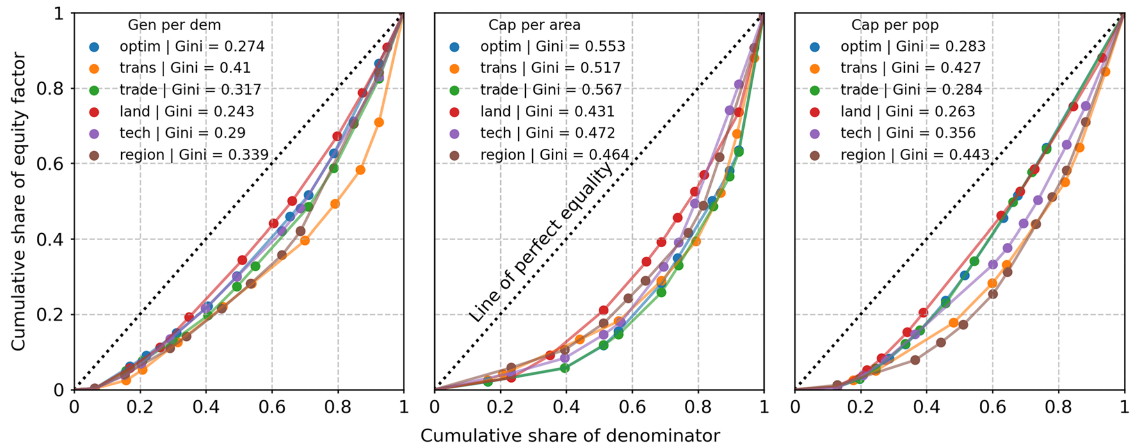


**Fig. 6 | Equity assessment of student-driven net-zero electricity system.** Student-driven scenarios assessed across three distributional justice definitions, including self-sufficiency (generation per demand), land-burden (capacity per area), and equality (capacity per population). (See Methods). A Gini value close to 0 indicates high equity, whereas a value near 1 denotes high inequity. The cumulative share of the denominator represents the contribution of the relative equity factor of each zone. The figure shows the results for the 2050 electricity system design. The map plots of denominators used for Gini coefficient calculation are shown in Supplementary Fig. 15.

benefits of a just and more inclusive energy transition. Inequality arises from concentrated investments in resource-rich areas and from the transmission of power to distant demand centers, resulting in disproportionate infrastructure burdens across zones. Unlike the most inequitable scenarios, landscape exclusion results in a more distributed VRE capacity, rather than concentration in specific zones (Fig. 5).

Our analysis indicates that student-influenced net-zero power system configurations do not necessarily increase equity with increased costs. For instance, a 25% increase in system cost worsens equity by 24 and 57% under self-sufficiency and equality principles (Fig. 4a, Fig. 6). Conversely, a cost decrease of up to 7% under transmission and trade choices also deteriorates equity by up to 50%. Figure 6 reveals that different scenarios result in varying equity levels within a given justice definition and do not align across different framings of distributional justice. The heatmap (Supplementary Fig. 14) illustrates how the equity score varies with changes in justice definitions. For instance, Oslo (NO03) performed best under the land-burden principle due to its small area, whereas all other zones outperformed Oslo under self-sufficiency and equality.

### Qualitative discussion and feedback on the net-zero systems designed by students' choices

To gather feedback on the modeling outcomes reflecting participants' choices, we held a session at one of the participating schools (see Methods) and presented the modeling results. Students largely reaffirmed their support for offshore wind and solar power, while deepening their understanding of the trade-offs and the necessity of compromises. The detailed student quotes are presented in Supplementary Table 7. Students viewed a high reliance on offshore wind as a pathway to sustainability, environmental preservation, and the avoidance of localized socio-political tensions. As one participant noted, "Offshore and solar makes sense to me." However, marine stakeholders' perspectives on offshore wind development are essential for building just offshore energy systems. Students were surprised by the prevalence of certain technologies they did not expect in modeling results, with one stating, "I am surprised there is so much onshore" (Q5-Q6). The reasons for their surprise were diverse, including considerations of costs, valuing nature, and social factors. While students generally adhered to the country's self-sufficiency, some desired to help other nations address climate change by increasing electricity exports (Q9-Q10).

Students foresee limited new job opportunities (Q11) due to potential strains on local economies stemming from decreased reliance on oil and gas exports in the net-zero electricity systems. The high system costs associated with regional preferences for VRE distribution appeared to influence students to reconsider these aspects, reflected in notes like, "Though we have esthetic/environmental demands, the cost is too high to consider all of these". The feedback session revealed several benefits: providing students with opportunities to reassess their choices (Q1-Q4), deepen their understanding of renewable electricity systems (Q13-14) and associated trade-offs (Q7-Q8), and address misconceptions commonly spread through social media—for instance, that excluding wind energy has minimal impact on the energy transition, that electricity trading among countries is unnecessary for achieving net-zero, and that wind turbines consume more electricity than they produce.

## Discussion and conclusion

The global drive to reduce GHG emissions has led, and will continue to lead, to increased deployment of solar and wind installations. These often provoke economic conflicts and acceptance challenges due to visual, auditory, environmental impacts, and land-use considerations. The proposed workshop-informed modeling framework provides a template for expanding educational outreach and meaningfully engaging diverse community groups. Our results supplement the insights from academic literature and policy documents, addressing themes, such as self-sufficiency (trade scenario), nature protection (land scenario), willingness to accept/pay (technology scenario), and empowerment of underrepresented groups[20,27,33,46].

We show that excluding landscapes opposed by students could increase the LCOE by roughly 10% to meet the 2050 demand forecast for Norway due to onshore wind being replaced with solar PV and offshore wind (Fig. 2). Compared to a Great Britain-based study, where public sensitivity to visual impacts increased total system costs by up to 14.2%, students' preferences in Norway have a smaller effect[47]. Moreover, the results closely align with current policy discussions and the Norwegian government's plan to achieve offshore wind capacity of 30 GW, including 1.5 GW from floating turbines, by 2040. This target would offer a counterbalance to the twofold reduction in the country's onshore wind capacity potential, as indicated in our results[48].

Student preferences reconfigured optimal technology compositions for the 2050 net-zero electricity system: onshore wind decreased from 40% to 0% (under the most restrictive scenario); largely substituted by offshore wind increasing from 9 to 82%; solar maintained 20–50% deployment across scenarios; new energy storage ranged from 70 to 125 GWh; and transmission network capacity expanded from 55 to 96 GW. The students' increased support for rooftop solar can be applied to areas with high solar potential, such as southern and eastern Norway, to help fill the gap left by reduced onshore wind. Although solar PV upfront costs are relatively low compared to other VRE, adoption issues in Norway may stem from insufficient policy support addressing the price-production mismatch, where electricity prices are very low during the summer when solar PV output is higher and high in the winter when PV output is lower, thereby lowering incentives for rooftop solar investment.

Our insights indicate that the net-zero energy system envisioned by young people does not necessarily deviate substantially from policymakers' perspectives or techno-economic ESM scenarios[42]. This suggests youth empowerment as a critical strategy for fostering broader community support and mitigating the growing negative sentiment towards VRE. While alignment between policymakers and youth in advocating for extensive development of offshore wind installations may generally strengthen public trust and support, it also risks generating localized socio-political tensions due to regional inequities and visual and environmental impacts on coastal communities. These installations would be concentrated in western and southern Norway, where hydropower resources already exist and export to demand centers (Fig. 5 & Fig. 6).

Equity outcomes of student-driven scenarios varied substantially depending on the definitions of justice. The land scenario achieved the most equitable distribution, while the trans scenario was the most inequitable, with cost variation between the least and most equitable scenarios of ~15%. Moreover, the equity of the most expensive region scenario worsens by up to 57%, revealing that costly systems are not necessarily equitable. The open question of how equitable the resulting unified net-zero system will be is largely influenced by the definitions of distributional justice. This sensitivity of new VREs' regional benefits and burdens to definitions of distributive justice illustrates that equity depends not only on the location of VRE infrastructure but also on what different groups and communities perceive as just, e.g., who owns energy infrastructure, wellbeing, job creation, and local environmental degradation[49]. Given that Norwegian youth exhibit more favorable attitudes towards VRE than older generations[50], involving young people's representatives in decision-making processes may help foster local acceptance of new solutions to conflicts associated with VREs. Young people residing in coastal regions may not necessarily share such preferences, as those in the sampled regions (Eastern and Southeastern Norway), shaped by direct experience with energy infrastructure. The strong offshore preference we document may partly reflect limited exposure to offshore wind developments in the sampled regions (See Supplementary Note 1). Future research should engage youth across all regions to assess whether geographic location systematically shapes preferences or whether our findings reflect broader generational values. Moreover, we suggest combining the national focus of the current study with local considerations through regional case studies to ensure that offshore solutions are truly equitable.

We demonstrate how effective communication, empowerment, and collaborative decision-making with underrepresented groups can operationalize procedural justice and inclusive solutions, as differences in stakeholder opinions may not be techno-economically difficult to reconcile. A mixture of avoiding and mitigating negative impacts, embedding new VRE installations within place-based value creation, and compensating for unavoidable impacts in a desired form can foster distributional justice. A feedback discussion session highlighted that climate actions must be approached as localized social issues (community-based), given Norway's diverse cultural landscape, where a one-size-fits-all approach may not lead to effective policy implementation at local levels. This session also illustrated that co-designed modeling studies enable participants to reflect on choices and assumptions. For example, students reconsidered some onshore wind restrictions after the modeling results revealed that these led to higher system costs. By meaningfully engaging diverse groups, such as youth, in decision-making processes, Norway can better navigate the challenges associated with the energy transition.

Although the scenarios can be tailored to local socio-political contexts, the framework employed in this study is applicable to other underrepresented groups and countries, especially in the global north, where discussions about the energy transition are part of broader political discourse due to increased negative public sentiment[18]. By integrating stakeholder preferences into ESM, non-cost values can be operationalized within techno-economic models. For instance, cost-only optimization cannot inherently preserve landscapes valued by communities, ensure regional equity in infrastructure distribution, or maintain local energy sovereignty. The proposed participatory modeling framework demonstrates how to incorporate such values systematically by translating preferences into binding constraints: landscape choices become spatial deployment restrictions; technology priorities set capacity-share limits; and regional choices define regional allocation caps. Moreover, local governments can develop guidelines that incorporate diverse groups' perspectives within the community, ensuring that new renewable installations align with national and regional plans and can actually be delivered on time, rather than being blocked or delayed, thus making the energy transition more costly. This strategic approach can help countries effectively navigate the socio-economic challenges associated with transitioning to sustainable energy systems.

## Methods

### Modeling framework: adaptation of highRES electricity system model

We provide detailed specifications of the highRES model adaptation for Norway. In this Norway-focused study, we modify the open-source high-temporal- and high-spatial-resolution Electricity System model (highRES), designed to assess high shares of variable renewables and explore flexibility options[38]. Utilizing perfect foresight of input data, highRES optimizes the spatial allocation of new VRE installations, operational decisions, transmission infrastructure, and storage technologies while minimizing the total system costs, encompassing annualized capital investments and annual operation and maintenance costs. In evaluating the costs associated with students' preferences, their choices were incorporated into the model through the constrained optimization approach explained below. The hybrid greenfield model does not account for existing solar- or wind-based installed infrastructure, except for hydropower, pumped hydro storage, and transmission infrastructure, including interconnections with other countries. Hydropower capacities remain fixed and are expected to remain so until 2050. We focused exclusively on battery-based energy storage, assuming that local battery production will gradually increase by 2050[45].

We exclude investment costs for existing infrastructure; however, we include fixed and variable operation and upkeep costs. The existing 5 GW of installed wind power capacity is excluded, assuming that these wind farms will be entirely replaced by 2050 due to their lifespan limits, allowing the model to determine whether new wind installations should occur at these locations. We adapt the highRES modeling framework for Norway by incorporating changes to model scenarios, reflecting the youth's preferences across different power system aspects. The modified version, highRES-Norway, and replication data are openly available.

The baseline scenario includes the highRES's implicit settings. We maintained Norway's interconnection capacity at its current level, as reported by Statnett, the Norwegian Transmission System Operator (TSO), with no projections for 2050[51]. In the base scenario, interconnection capacities are assumed to be utilized at one quarter of their rated capacity based on historical utilization rates[52]. Moreover, the base case reflects current regional transmission capacities, set as a lower bound to assess the impacts of grid expansion in line with students' choices. Transmission capacities between Norwegian counties as well as with other countries are given in the Supplementary Tables 3 and 4.

For analysis consistency, a fixed import and export price is assumed, based on 2020 hourly electricity prices from connected countries, weighted by the interconnector size. While Norways' administrative regions (called zones in this study) were restructured in 2024, we use pre-structuring boundaries of 11 regions due to the project's initial work and educational workshop preparations. We apply a system-wide carbon-emission limit of 0 gCO2-kWh across all demand years, thereby precluding carbon-emitting technologies, including carbon capture and storage. The core modeling framework is implemented using the workflow management system Snakemake, automating input data processing based on student choices across power system dimensions and generating all possible sequencing orders to integrate these preferences. The detailed core model structure is documented in the Referenced studies[38,42,53,54].

We use 2010 weather data input due to its challenging conditions—unusual cold and reduced precipitation—leading to high electricity demand and less hydropower production, which is Norway's primary electricity source[55]. ERA5 weather reanalysis climate data from ECMWF[56] are converted into time series for power system variables (i.e., capacity factors) using the xarray-based Python library Atlite[57]. Due to Norways' complex terrain, ERA5's 0.25 degree data insufficiently captures localized wind variations, possibly leading to wind power estimation inaccuracies. Therefore, a bias correction function is computed using historical wind power production data from the Norwegian Water Resources and Energy Directorate (NVE), comparing NVE historical production with ERA5 wind speeds at operational wind parks for each 30 ×30 km grid cell such that year-round distribution of capacity factors of both datasets matches[42]. This corrected data undergoes further exclusions in the workflow process before being put into the model.

For investment decisions regarding new VRE installations, the spatial level is set at the zonal level, with 30 × 30 km grid-cell weather data averaged at this level, excluding poorly performing cells with average capacity factors below thresholds—0.09 for solar, 0.15 onshore wind, and 0.20 offshore wind power[41]. Further exclusions are based on the World Database of Protected Areas, terrain with a slope over 15 degrees, elevations above 2000 m, and physical infrastructure (military areas, airports, glaciers, etc.). Additional exclusions are also applied based on buffers around urban fabric (2 km) and other infrastructure (5 km) for safety reasons[42]. These exclusions delineate the VRE deployment area available in the base scenario. Further exclusions in the base scenario grid cells are based on student landscape preferences, substantially altering the available input area. All exclusions are measured in area ($km^2$) and converted to solar and wind capacity potentials at zonal and national levels using the assumed conversion metric of 3 MW-$km^2$[47].

Like the weather year, the 2010 electricity demand time series serves as a baseline, augmented with future projections for 2030, 2040, and 2050. According to Norwegian TSO forecasts, the maximum Norwegian electricity demand in 2050 is projected at 260 TWh, up from 140 TWh in 2022, including demand from electric transport[45]. The increased demand is spatially distributed across zones at hourly temporal resolution using methods detailed in ref. 54 (Supplementary Fig. 15). The distribution of demand increases across different Norwegian sectors is detailed in Reference[54]. The technology cost parameters used in this study are depicted in Supplementary Table 2. We acknowledge that 2050 technology cost projections are uncertain and require sensitivity analysis, which is beyond the scope of this study, which focuses on participatory ESM.

Several assumptions underlying this study could impact the results. The exclusive focus on wind- and solar-based technologies reflects Norwegian governmental priorities without considering existing solar and wind power capacities in light of the 2050 net-zero projections. We expand electricity transmission capacity beyond current levels while respecting students' choices and aligning with existing infrastructure constraints. Interconnections with new countries were not envisaged; instead, enhancements to current interconnections were emphasized, with import/export costs assumed constant. Additional electricity system modeling assumptions are detailed in the Supplementary Note 1.

### Workshops-driven scenario framework

The methodological details of workshops are given in Supplementary Note 2. The educational workshops spanned a full day, featuring interactive activities specifically designed to foster meaningful participant engagement. By restructuring the modeling approach, we meaningfully engaged young people's perspectives across the entire ESM process. This inter- and multidisciplinary study involved psychologists, political scientists, sociologists, biologists, VRE scientists, and energy system modelers, ensuring workshops facilitated collective learning and provided context for informed energy choices.

The questionnaire was aligned with the energy system planning model and addressed several power system aspects, including choices among different VRE and between energy storage and electricity trading (import/export), transmission infrastructure expansion, various techno-economic choices, and preferences regarding regional and landscape settings for new VRE. These core aspects are crucial for capturing energy justice considerations associated with evolving power systems[33]. It is worth mentioning that while the workshop activities involved collaborative learning in small groups, the questionnaires were completed individually, preserving individual agency in preference expression. The group format enabled shy students to contribute ideas within safer peer settings before group representatives presented consolidated perspectives in plenary discussions. Group compositions were changed between activities to prevent any single student from dominating deliberations throughout the workshop. Following a detailed assessment of workshop data[43], six main scenarios were developed to evaluate the impact of students' preferences on snapshots of a net-zero electricity system design for Norway. A range of scenarios was simulated based on prioritization and the incremental integration of students' choices, alongside stepwise exclusions of landscapes with which they disagreed. Supplementary Table 5 presents exemplary scenarios that reflect young people's viewpoints.

The baseline scenario is a model-based optimization benchmark for evaluating the impact of student choices. It includes default exclusions discussed in the previous section and maintains current electricity transmission and import/export capacities. The transmission (trans) scenario reflects student preferences regarding whether: 1) to extend the grid, and 2) to choose between expansion with overhead or underground power lines. To incorporate students' choices, current zonal transmission capacities were set as lower bounds, and a transmission equation (Eq. 1) was added to ensure new capacities encompass the desired percentage of overhead and underground cables:

$$\sum_{z,z\prime} subsurface \geq \alpha . \left[ \sum_{z,z\prime} pcap - \sum_{z,z\prime} cap0 \right] \tag{1}$$

Given the model's prioritization of least-cost overhead investments, the equation ensures proportions of subsurface power lines between zones ($z$) in the transmission expansion are maintained by subtracting existing capacities ($cap0$) from total capacities ($pcap$). *Alpha* denotes the percentage of participants' support for underground power lines, ensuring that at least this proportion is embodied within the net-zero power system.

The trade scenario reflects young people's choices regarding electricity trade with other countries to address the challenges of renewable energy variability. Regardless of import/export levels, students favored self-sufficiency—equating imports with exports—and local energy storage. To reflect participants' desires for import/export in trade scenarios, the upper bounds of interconnection utilization rates were varied up to threefold, assuming full utilization without new power line investment costs. To reflect the principle of self-sufficiency, the electricity balance equations (Eq. 2) were redefined to ensure that annual import and export levels matched, thereby enabling more efficient optimization of power dispatch.

$$\begin{aligned} \sum_{tech} G + \sum_{storage} (out - in) + \sum_{trans} (in - out) = Demand_h \\ + Export_h \; subject\ to: \sum_h Export_h = \sum_h import_h \end{aligned} \tag{2}$$

Here, import is assumed to be part of generation technologies ($G$), and export is added to demand. With maintaining self-sufficiency, total annual electricity trade levels were incrementally increased up to threefold to evaluate the impact, reflecting participants' support for helping other countries in their energy transition.

Transmission and trade scenarios were further simulated across three transmission categories (underground, overhead, and fixed transmission lines) and two trade categories (current-level limits and two- and three-times the current level), as the majority of students' selections fell into these categories (Supplementary Figs. 8–10)[43]. For the primary analysis, scenarios involving underground transmission and electricity trade at twice the current levels were selected, based on their prevalence among students and their representation of moderately ambitious energy transition strategies.

The land scenario reflects students' preferences for landscapes that favor or oppose VRE installations. The assessment indicated a strong preference for installations in sea, mountain, and vegetated areas, while placement in forests, agricultural lands, and residential areas was strongly opposed. Landscapes with a median value of less than 5 on a 9-point Likert scale were interpreted as indicating substantial opposition to installing new VRE and were therefore excluded from land scenarios for future VRE deployment[3,47]. The high-resolution Norwegian land data from the Norwegian Institute of Bioeconomy Research and the CORINE data were used to spatially exclude grid cells based on landscape preferences over the base scenario[58,59]. These exclusions, detailed earlier, lead to substantial changes in the available areas for new capacity installations and in the available generation capacity potential by technology.

The technology (tech) scenario reflects the students' technology choices for achieving a net-zero electricity system. The well-known discrete choice approach was employed to understand the youth's preferences regarding VRE[43]. Based on the quantitative assessment, preference levels for each technology were translated into aggregated upper limits on new capacity installations within the national VRE capacity mix (Eq. 3). For offshore wind, the ratio of fixed to floating installations was optimized since it was difficult for students to differentiate between them.

$$pcap_i \leq \beta_i \sum_j pcap_j \tag{3}$$

Where *pcap* represents the new capacity of technology type *i*, *beta* is the preference coefficient derived from participants' preferences through discrete choice analysis, and *j* represents the set of VRE technologies. Preference coefficients reflect the percentage of participants who choose the particular VRE, ensuring that its proportion in the new VRE capacity mix does not exceed the specified limit. For instance, if the model includes onshore wind, its proportion in the new capacity mix must not exceed 23.5%.

The regional (region) scenario interprets students' choices about appropriate wind and solar farm installation zones. The prior method was used to translate preferences into upper limits on new capacity installations per zone and technology (Eq. 4). For instance, preference levels for solar (~13%) and onshore wind (~10%) in Oslo delimit new capacity installations not exceeding these values relative to the aggregated national installations. Accordingly, depending on the capacity potential of each technology, the model may select installations in Oslo, subject to participants' preferences.

$$pcap_{i,r} \leq \gamma_{i,r} \cdot pcap_i \tag{4}$$

Where *pcap* signifies the new capacity of technology *i* in region *r*, while *gamma* represents the technology's preference coefficient for a given region derived from students' choices. For example, if the model chooses onshore wind capacity in Oslo, it must not exceed 10%. This scenario is notably conservative, and the model struggles to achieve optimization due to tight zonal constraints. Despite workshop materials and questionnaires being tailored to highRES model characteristics to minimize assumptions while translating students' outputs, we acknowledge potential bias arising from interpreting and analyzing the workshop results.

### Equity evaluation

Research indicates that equity within energy systems varies considerably depending on how the burdens and benefits of energy infrastructure are distributed[41]. Beyond establishing an appropriate definition, another crucial aspect involves deciding what should be distributed equitably, such as the allocation of new technology capacity installations, emission rights, or job opportunities. We adopted three principles that are most pertinent for analysis at the national scale. For land-burden and equality principles, the electricity system's installed capacities (both new and existing) serve as the equity factor, weighted against the zones' total areas and populations. The consideration of existing electricity infrastructure is vital in Norway's context, particularly since hydropower is concentrated primarily in specific zones. For the self-sufficiency principle, total electricity generation is treated as an equity factor, weighted by annual electricity demand, since generation takes precedence over installed capacity under this principle. Supplementary Fig. 15 illustrates the spatial distribution of denominators used for the justice definitions considered. The study utilizes the latest available descriptive statistics for population and areas from[52].

To evaluate the distribution of burdens (i.e., VRE capacities and electricity production) across zones and the impact of student choices on equity, burdens are plotted on a Lorenz curve in an ordered weighted format, with each point representing a zone. The divergence between the straight line and the Lorenz curve provides insight into the equity of a given preference scenario, facilitating the calculation of Gini coefficients. This metric frequently features in energy system analyzes to gauge inequalities, specifically in assessing how evenly the burden of new VRE installations is distributed[60]. The Gini coefficient is the mean difference from all observed quantities. The detailed mathematical interpretation of the Gini coefficient can be found in Reference[41]. Having calculated the Gini index, one can determine the sensitivity of the spatial allocation of VRE capacities to regional equity. It is worth mentioning that the relationship between Gini variables is nonlinear and, hence, cannot be incorporated into a linear optimization model. Instead, Gini values are calculated post-processing to consider the different framings of distributional justice.

### Feedback session methodology

To ensure students comprehended the connection between their questionnaire responses and modeled electricity system outcomes, feedback sessions employed a scaffolded approach. First, students used an interactive online tool[61] to design their own European electricity system, selecting technology contributions while observing real-time impacts on climate emissions, air quality, land use, electricity costs, and employment. Each group presented its design choices, explaining the trade-offs they prioritized, the objectives they sacrificed, and the decisions that proved most difficult to reconcile. This interactive activity set the stage for discussing highRES results reflecting students' preferences.

Subsequently, we systematically presented the modeling results: landscape-exclusion impacts, technology-composition shifts, system-cost changes, and regional capacity allocations. Each result was presented interactively rather than as a passive lecture, with students encouraged to voice observations, ask questions, and discuss implications. Students demonstrated comprehension by identifying connections between their preferences and offshore dominance, discussing why some regions received no new capacity, or whether cost increases justified the environmental priorities.

### Limitations and future work

While our results demonstrate the feasibility and potential of using school workshop-informed modeling to elicit underrepresented groups' participation in designing the future net-zero energy system, we suggest extending this work in two ways: by increasing representation and by conducting follow-up sessions. A next step to ensure broader youth representation involves expanding the geographic range to cover central and Northern counties, as well as relatedly, different segments, such as coastal, mountain, or Sami communities. Comparing the reasoning and the resulting scenarios, preferably by organizing discussion rounds across the country, is expected to help researchers and young people better understand the different perspectives of the energy transformation. Such an approach highlights the value of youth-informed scenarios as a tool for fostering future-oriented thinking and inclusive participation.

Although participatory modeling can inform participants' envisioned future electricity systems, attitudes toward renewable energy often shift when projects move from abstract concepts to specific siting decisions with tangible local impacts[62]. Our framework documents what informed stakeholders prioritize in principle but cannot predict responses to specific project proposals where additional factors—such as trust in developers, perceived procedural fairness of the approval process, local economic benefits, and proximity to individual homes—become salient.

While our study focused on electricity generation due to its central role in landscape change and its visibility in public discourse, future research could adopt a more holistic energy system perspective, integrating heating decarbonization (heat pumps, district heating), transport electrification infrastructure, and industrial energy pathways. Such integration would provide students with a holistic view of how heating and transport electrification drive growth in electricity demand, potentially affecting their preferences.

Yet the apparent precision and accuracy of such models can obscure the inherent uncertainties embedded in their underlying assumptions. Both the techno-economic and socially-determined parameters are influenced by normal fluctuations and larger events like pandemics, wars, tariffs, extreme climate events, terrorism, sharp political shifts nationally or abroad, technological failures, unforeseen impacts, and breakthroughs. Follow-up engagement processes will therefore be essential to understanding how such unexpected and large-scale events shape preferences and scenarios' outcomes.

**Reporting summary**

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

## Data availability

All the input data needed to replicate the results are available at https://doi.org/10.5281/zenodo.15401853. The detailed workshop methodology and modeling questionnaire used are available in Ref[43]. The workshop materials, including interactive activities and scripts, are openly available at GitHub (https://github.com/JavedMS/Mapping_Workshops_EFF.git). High-resolution Norwegian land data used for land exclusions is openly available at[58].

## Code availability

The modified version of the highRES electricity model used in this paper is open-source and available on GitHub (https://github.com/JavedMS/highRES-Norway.git), including the model formulation, results analysis scripts, and the modified model documentation describing the changes from previous versions.

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## Author contributions
Muhammad Shahzad Javed: conceptualization, methodology, data curation, formal analysis, visualization, writing—original draft; Karin Fossheim: conceptualization, methodology, data curation, writing—review & editing; Maximilian Roithner: methodology, visualization, writing—review & editing; Matylda N. Guzik: conceptualization, writing—review & editing,

funding acquisition; James Price: methodology, visualization, writing—review & editing; Beate Seibt: conceptualization, data curation, writing—review & editing, project administration, funding acquisition; Marianne Zeyringer: conceptualization, methodology, data curation, visualization, writing—review & editing, supervision, project administration, funding acquisition.

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## Competing interests

The authors declare no competing interests.

## Additional information

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**Correspondence** and requests for materials should be addressed to Muhammad Shahzad Javed.

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