A perspective on equity implications of net zero energy systems

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1. Introduction

In order to address climate change, humanity must act soon to limit the atmospheric concentration of greenhouse gases (GHG) and reduce energy-related GHG emissions. There has been considerable attention devoted to the technological, economic, policy and societal changes needed during an energy transition, as well as an emerging literature, including in this journal issue, aiming at understanding how a net zero energy system will be composed. There is also an emerging literature on energy equity, yet relatively little attention has been paid to the implications for energy equity and distributional consequences specifically associated with net zero energy systems. In this perspective article, we highlight some of the key issues, uncertainties and paths forward for research to understand the equity implications of net zero energy systems.

In recent years, there has been an increase in attention to environmental justice, equity and distributional effects associated with environmental questions, and specifically associated with the provision of energy services and the transition to a low-carbon society.[1] There is no single globally agreed upon definition for environmental justice and equity, nor for energy equity. The U.S. Environmental Protection Agency (EPA) defines environmental justice in terms of protecting all people from negative environmental consequences and giving equal access to environmental decision-making.[2] Energy equity encompasses these ideas, and goes farther, recognizing that the consequences of the energy system reach beyond the environmental into economic and social spheres, and acknowledging the importance of the distribution of energy system benefits as well as costs.[3]

Our current energy systems are inequitable across several dimensions. There has been a great deal of attention given to some aspects of energy equity in the context of climate change, such as issues related to global energy access[4] and jobs,[5] especially possible disruption of current jobs in the fossil fuel industry. While these issues are important, in this perspective we emphasize some frequently overlooked considerations, including racial and income disparities in the distribution of benefits and costs, beyond employment changes, from the transition to net zero. We discuss

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[1] Sovacool, B. K. (2021). Who are the victims of low-carbon transitions? Towards a political ecology of climate change mitigation. *Energy Research and Social Science*, *73*, 101916. https://doi.org/10.1016/j.erss.2021.101916

[2] US Environtmental Protection Agency (2021). Environmental Justice. https://www.epa.gov/environmentaljustice

[3] Carley, S. and Konisky, D.M. (2020). The justice and equity implications of the clean energy transition. *Nature Energy,* 5(8), pp.569-577.

[4] B. Tarekegne, (2020) Just electrification: Imagining the justice dimensions of energy access and addressing energy poverty, *Energy Research & Social Science*, 70, 101639; D. Nock, T. Levin, E. Baker, (2020). Changing the policy paradigm: A benefit maximization approach to electricity planning in developing countries, *Applied Energy*. 264, 114583. https://doi.org/10.1016/j.apenergy.2020.114583; N.D. Rao and S. Pachauri (2017) Energy access and living standards: some observations on recent trends, *Environ. Res. Lett.* **12** 025011

[5] Jolley, G. J., Khalaf, C., Michaud, G. & Sandler, A. M. (2019). The economic, fiscal, and workforce impacts of coal-fired power plant closures in Appalachian Ohio. *Reg. Sci. Policy Pract.*11, 403–422; Carley, S., Evans, T. P. & Konisky, D. M. (2018). Adaptation, culture, and the energy transition in American coal country. *Energy Res. Soc. Sci.* 37, 133–139; Lobao, M., Zhou, M., Partridge, M. & Betz, M. (2016). Poverty, place, and coal employment across Appalachia and the United States in a new economic era. *Rural Sociol.* 81, 343–386

three aspects of energy equity under current and net-zero energy systems: 1) energy burden and energy insecurity; 2) health consequences from air pollution; and 3) decision making power. We focus largely on issues around internal inequities in developed countries, but note that many of these inequities exist in developing countries as well.

A net zero energy system will be very different from today's system; moreover, the range of net zero systems imagined and evaluated in the literature are very different from each other.[6] There is much uncertainty on what net zero energy systems will look like globally and for different regions of the world. It is likely that most regions will move towards electrification of end-uses and transportation and rely to a large extent on renewable energy sources. There are, however, many possible net zero systems, including those with significant amounts of nuclear, bioenergy, and even fossil energy with CCS.[7] The degree to which the dimensions discussed above are important depends somewhat on the eventual realization of net zero systems around the world.

2. Overlooked considerations for net zero energy systems

The transition to a net zero energy system will require dramatic transformation of the energy system. It also provides an opportunity to develop a more equitable energy system. In this section, we discuss examples of inequity in current energy systems, and barriers to a just and equitable net zero energy system.

2.1 Energy burden and energy insecurity:

People with lower income pay higher proportions of their income for energy, in the US[8] and in developing countries[9], and may have higher bills due to poorly constructed housing and poor energy efficiency.[10] These inequities are deepened when looking at race and ethnicity. For example, in the US, due to historic redlining and other forms of systemic segregation, neighborhoods with high proportions of Black, Indigenous, and other People of Color (BIPOC) have homes that require more energy to keep warm or cool.[11] These inequities have been underlined in the recent COVID crisis: 25% of respondents in a 2020 survey of low-income Americans could not pay their energy bills in the prior year; when broken down by race, this was true of 30% of Black households and only 20% of white households.[12]

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[6] J. DeAngelo, I. Azevedo, J. Bistline, L. Clarke, G. Luderer, E. Byers, and S.J. Davis. (2021) Net-zero CO_2 emissions energy systems in scenarios, *Under review*

[7] Energy Innovation. (2020). "Net-Zero Emissions Scenario." Policy Solutions. https://us.energypolicy.solutions/scenarios/home; Haley, B., R. Jones, G. Kwok, J. Hargreaves, J. Farbes, and J. Williams. (2019). 350 PPM Pathways for the United States. U.S. Deep Decarbonization Pathways Project. Evolved Energy Research; Larson, E., C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, S. Pacala, et al. (2020). Net-Zero America by 2050: Potential pathways, deployments and impacts. Princeton, NJ: Princeton University.

[8] C.E. Kontokosta, V.J. Reina & B. Bonczak (2020). Energy Cost Burdens for Low-Income and Minority Households, *Journal of the American Planning Association*, 86:1, 89-105, DOI: 10.1080/01944363.2019.1647446

[9] Winkler, H., Simões, A.F., La Rovere, E.L., Alam, M., Rahman, A. and Mwakasonda, S., 2011. Access and affordability of electricity in developing countries. *World Development*, *39*(6), pp.1037-1050

[10] Reames, T.G., (2016). Targeting energy justice: Exploring spatial, racial/ethnic and socioeconomic disparities in urban residential heating energy efficiency. *Energy Policy*, 97, pp.549-558

[11] Reames (2016). Kontokosta et al. (2020).

[12] Memmott, T., Carley, S., Graff, M., & Konisky, D. M. (2021). Sociodemographic disparities in energy insecurity among low-income households before and during the COVID-19 pandemic. *Nature Energy*, *6*(2), 186–193.

The equitable affordability of energy services under net zero energy systems will partly depend on the design, resources and technology composition of such systems. If the net zero system is more costly, as anticipated by some studies,[13] this may deepen economic inequities, resulting in energy "haves and have-nots." If higher energy prices lead to a need to reduce energy use, then those who live in poorly insulated homes will be even less comfortable. Net zero systems with high penetration of intermittent renewables may rely on demand response programs to assist with grid integration.[14] Recent research has found inequities in demand response programs, with Hispanic households showing not only negative income effects but negative health impacts as well.[15] Programs designed to promote retrofits, zero carbon emissions technologies, and energy efficiency, no matter how well-meaning, will require a careful design to avoid backfiring with unintended consequences.[16]

2.2 Health impacts:

Some recent studies focus on the impacts of air pollution by income and/or race & ethnicity in the context of energy systems, with much of the current work being done in the US context. Thind et al. (2019) address the air pollution effects associated with the provision of electricity, and estimate how premature mortality from electricity generation varies by race, income, and geography, as well as understanding which US states import or export mortality effects.[17] They show that Black/African American people have higher premature mortality from the air pollution created in the process of producing electricity than other races or ethnicities, and that such a difference occurs for all income ranges. Tessum et al. (2019) find that pollution exposure for Black and Hispanic people is 56% and 63% higher than the exposure caused by their own electricity consumption.[18] Recent work shows that BIPOC are exposed to more pollution, even accounting for income and wealth, possibly due to the lack of political power in marginalized communities.[19] This outdoor pollution combines with poor indoor air quality due to low quality housing and low quality heating fuel, all working together to negatively impact the health of low-

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[13] Deason, W. (2018). Comparison of 100% renewable energy system scenarios with a focus on flexibility and cost. *Renewable and Sustainable Energy Reviews*, 82, pp.3168-3178.

[14] Tabar, V.S., Hagh, M.T. and Jirdehi, M.A., 2021. Achieving a nearly zero energy structure by a novel framework including energy recovery and conversion, carbon capture and demand response. Energy and Buildings, 230, p.110563; Davis, S.J., Lewis, N.S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I.L., Benson, S.M., Bradley, T., Brouwer, J., Chiang, Y.M. and Clack, C.T., 2018. Net-zero emissions energy systems. *Science*, *360*(6396).

[15] White, L.V. and Sintov, N.D., (2020). Health and financial impacts of demand-side response measures differ across sociodemographic groups. *Nature Energy*, 5(1), pp.50-60; Fell, M.J. (2020). Just flexibility?. *Nature Energy*, 5(1), pp.6-7

[16] Burns, R. (2021). The Subprime Solar Trap for Low-Income Homeowners. Bloomberg. https://www.bloomberg.com/news/features/2021-04-06/the-subprime-solar-trap-for-low-income-homeowners

[17] Thind, M.P.S., Tessum, C.W., Azevedo, I.L., Marshall, J.D., (2019). Fine particulate air pollution from electricity generation in the US: health impacts by race, income, and geography. *Environmental Science & Technology.*

[18] Tessum, C. W., Apte, J. S., Goodkind, A. L., Muller, N. Z., Mullins, K. A., Paolella, D. A., … Hill, J. D. (2019). Inequity in consumption of goods and services adds to racial-ethnic disparities in air pollution exposure. *Proceedings of the National Academy of Sciences of the United States of America*, 116(13), 6001–6006. https://doi.org/10.1073/pnas.1818859116

[19] Carley, S. and Konisky, D.M., 2020. The justice and equity implications of the clean energy transition. *Nature Energy*, 5(8), pp.569-577; Banzhaf, S., Ma, L. and Timmins, C., (2019). Environmental justice: The economics of race, place, and pollution. *Journal of Economic Perspectives*, 33(1), pp.185-208; Wilson, P., Adrian, J., Wasserman, K., Starbuck, A., Sartor, A., Hatcher, J., Fleming, J. and Fink, K., (2012). Coal blooded: Putting profits before people.

income and BIPOC.[20] While studies of disparities are less common in developing countries, some recent studies have shown that polluting plants are more likely to be located in areas with low socioeconomic status.[21]

Pollution may get worse for some groups under net zero. The use of centralized combustion plants implies the existence of local pollution hotspots, unless there are strict pollution controls, and yet many net zero scenarios include electricity from combustion of natural gas or biomass, especially in conjunction with carbon capture and storage (CCS).[22] In particular, many net zero scenarios include BECCS as a negative emissions technology.[23] Scenarios that rely heavily on carbon removal pose a threat to health and equity for those who live near combustion sites.[24] Polluting combustion facilities in general, and bioenergy in particular, are disproportionately sited in environmental justice communities.[25] If this historical trend continues, then even as the grid becomes less reliant on polluting fossil fuels, those who can least afford it may be more exposed to particulate matter. A prospective study by Diana et al. (2021) finds that, in the absence of attention to environmental justice issues, a 20% reduction in carbon emissions in California could lead to more than a tripling of electricity-related co-pollutant damage in Black communities.[26]

On the other hand, some studies suggest that combustion plants may be largely retired in a net zero energy system (see Jenkins et al [ref 22] and DeAngelo et al [ref 6] for multi-study comparisons). While this would reduce the threat of local pollution for vulnerable communities, it would not eliminate it. For example, hazardous materials in solar waste provide an environmental justice threat,[27] as does the lifecycle of nuclear power.[28]

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[20] Liddell, C. and Morris, C., (2010). Fuel poverty and human health: a review of recent evidence. *Energy Policy*, 38(6), pp.2987-2997; Gould, C.F., Chillrud, S.N., Phillips, D., Perzanowski, M.S. and Hernández, D., (2018). Soot and the city: Evaluating the impacts of Clean Heat policies on indoor/outdoor air quality in New York City apartments. *PloS one*, 13(6), p.e0199783.

[21] Hajat, Anjum; Hsia, Charlene; O'Neill, Marie S. Socioeconomic Disparities and Air Pollution Exposure: a Global Review. *Current Environmental Health Reports* (2015), 2 (4), 440-450

[22] Jenkins, J.D., Luke, M. and Thernstrom, S., 2018. Getting to zero carbon emissions in the electric power sector. *Joule*, *2*(12), pp.2498-2510.

[23] Rosa, L., Sanchez, D.L. and Mazzotti, M., 2021. Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. *Energy & Environmental Science*, *14*(5), pp.3086-3097

[24] Healey, P., Scholes, R., Lefale, P. and Yanda, P., 2021. Governing Net Zero Carbon Removals to Avoid Entrenching Inequities. *Frontiers in Climate*, *3*, p.38.

[25] Koester, S. and Davis, S., 2018. Siting of wood pellet production facilities in environmental justice communities in the Southeastern United States. *Environmental Justice*, *11*(2), pp.64-70; Shrader-Frechette, K.S. and Preisser, W.C., 2013. Renewable Technologies and Environmental Injustice: Subsidizing Bioenergy, Promoting Inequity. *Environmental Justice*, *6*(3), pp.88-93.

[26] Diana, B., Ash, M., & Boyce, J. K. (2021). Green for All: Integrating Air Quality and Environmental Justice into the Clean Energy Transition. Political Economy Research Institute. https://peri.umass.edu/publication/item/1408-green-for-all-integrating-air-quality-and-environmental-justice-into-the-clean-energy-transition

[27] Kumar, A. and Turner, B., (2020). Sociomaterial solar waste: afterlives and lives after of small solar. In Bombaerts G., Jenkins K., Sanusi Y., Guoyu W. (eds) *Energy Justice Across Borders* (pp. 155-173). Springer, Cham.

[28] Malin, S.A. and Alexis-Martin, B., 2020. Assessing the state of uranium research: Environmental justice, health, and extraction. *The Extractive Industries and Society*, *7*(2), pp.512-516

2.3 Ownership of assets:

The above examples focus largely on the distribution of negative externalities. A net zero system also provides opportunity to change the structure of ownership of energy assets and to include marginalized communities in energy decisions that impact them. For example, it is very likely that most net zero energy systems will rely on electricity from renewable energy sources; one realization of that includes large amount of rooftop solar.[29] In the absence of intentional policies, the high upfront cost of solar PV makes it likely that ownership of rooftop solar will be concentrated in wealthier communities with low-density and high rates of home ownership. Indeed, research has found that to date, solar PV has been predominantly adopted by high income and majority-white segments of the population.[30] This disparity can worsen financial inequity, since those with higher income will reap the benefits of reduced energy costs. This can also worsen inequities around decision-making and agency, as lower income urban dwellers are cut out of participating in an important way in the energy system; owners of assets may have more voice in decision-making.[31]

Subsidies to encourage adoption of rooftop solar make this worse and are highly regressive.[32] Subsidies paid by all consumers increase the energy burden of the poor; yet they go to homeowners with roofs and sunshine, not to urban dwellers in multi-unit buildings in congested, shaded areas. Net-metering provides an additional bonus to those who can afford rooftop solar, by moving the costs of maintaining the grid to those who cannot.[33] These inequities may be exacerbated by reliability-motivated moratoriums on solar permitting in places where the grid is stressed by large amounts of this intermittent technology; such regulations reinforce the value of early adoption. Lifetimes of solar panels can be 25 years or more, so the policies for rooftop solar adoption set today will determine the ownership patterns for solar in the net zero energy system.

Another example is the adoption of smart meters, which may be important in net zero systems for managing energy demand. Smart meters enable rapid identification of power outages, more accurate billing, easier switching between carriers, and, crucially, participation in demand response programs.[34] While current demand response programs do not provide many, if any,

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[29] Hawken, P. ed., 2017. *Drawdown: The most comprehensive plan ever proposed to reverse global warming*. Penguin.

[30] Vaishnav, P., Horner, N., Azevedo, I.L., (2017). Was it worthwhile? Where have the benefits of rooftop solar photovoltaic generation exceed the cost? *Environmental Research Letters*, 12(9), 094015; Sunter, D. A., Castellanos, S., & Kammen, D. M. (2019). Disparities in rooftop photovoltaics deployment in the United States by race and ethnicity. *Nature Sustainability*, 2(1), 71–76. https://doi.org/10.1038/s41893-018-0204-z

[31] A report related to women in developing countries includes some research indicating that ownership of assets increases voice in public decision-making: Domingo, P., Holmes, R., O'neil, T., Jones, N., Bird, K., Larson, A., Presler-Marshall, E. and Valters, C., 2015. Women's voice and leadership in decision-making. Overseas Development Institute. https://odi.org/en/publications/womens-voice-and-leadership-assessing-the-evidence/

[32] Nelson, T., Simshauser, P. and Kelley, S., (2011). Australian residential solar feed-in tariffs: industry stimulus or regressive form of taxation?. *Economic Analysis and Policy*, *41*(2), pp.113-129; Smith, J.T., Patty, G. and Colton, K., (2018). Net Metering in the States: A primer on reforms to avoid regressive effects and encourage competition. Center for Growth and Opportunity at Utah State University.

[33] Burger, S.P., Knittel, C.R., Pérez-Arriaga, I.J., Schneider, I. and Vom Scheidt, F., 2020. The efficiency and distributional effects of alternative residential electricity rate designs. *The Energy Journal*, *41*(1).

[34] Sovacool, B.K., Kivimaa, P., Hielscher, S. and Jenkins, K., 2017. Vulnerability and resistance in the United Kingdom's smart meter transition. *Energy Policy*, *109*, pp.767-781.

benefits to the participants, there is great potential for them to do so.[35] If smart meters are unfairly distributed due to a high upfront cost or lack of trust among historically mistreated consumers, then marginalized communities may lose out on these potential benefits.

While the issue has not been studied in detail, the same set of concerns described for solar and smart meters could arise in the context of other end-use technologies and services, such as electrified transportation, new forms of mobility or delivery services, and behind-the-meter storage devices.

3. Research needs regarding equity implications of net zero energy systems

3.1 The need to define and quantify energy equity.

First, we need to think carefully about how to measure energy equity. We know that what is measured matters.[36] But equity and justice are challenging concepts to agree on and to quantify. Metrics should speak to the very people who have been marginalized in the past.[37] These metrics must extend to the multiple dimensions of energy equity and justice, including distributive (around the "distribution of benefits and ills" across society), recognition (all voices must be "fairly represented, … free from physical threats and …offered complete and equal political rights"), and procedural justice (access to decision-making processes).[38] There has been some attention to distributive justice among the community working on large scale energy modeling issues; many of these now linked to the emerging effort called "Macro-Energy Systems" and its community.[39] Other dimensions of justice and equity are also important and must be measured in order to be addressed.

A report from the Initiative for Energy Justice has provided an inventory of dozens of existing metrics covering issues such as energy access and affordability; procedural justice and democracy; economic participation and community; and health and environmental impacts.[40] The large number of metrics highlights the fact that equity and justice are complex, multi-dimensional concepts. The energy systems research community faces a challenge in distilling such metrics down to a tractable number that can be used in meaningful ways, and to go beyond the distributional metrics that have been represented so far.

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[35] Dahlke, S. and Prorok, M., 2019. Consumer savings, price, and emissions impacts of increasing demand response in the Midcontinent electricity market. *The Energy Journal*, *40*(3).

[36] Stiglitz, J.E., Jean-Paul Fitoussi, Martine Durand. (2019). *Measuring what counts: The global movement for well-being*. The New Press.

[37] Agbim, C., Araya, F., Faust, K.M. and Harmon, D., (2020). Subjective versus objective energy burden: A look at drivers of different metrics and regional variation of energy poor populations. *Energy Policy*, 144, p.111616.

[38] Jenkins, K., McCauley, D., Heffron, R., Stephan, H. and Rehner, R., (2016). Energy justice: a conceptual review. *Energy Research & Social Science*, *11*, pp.174-182.

[39] Levi, P.J., Kurland, S.D., Carbajales-Dale, M., Weyant, J.P., Brandt, A.R. and Benson, S.M., 2019. Macro-energy systems: Toward a new discipline. *Joule*, *3*(10), pp.2282-2286.

[40] Lanckton, T., & DeVar, S. (2021). Justice in 100 Metrics: Tools for Measuring Equity in 100% Renewable Energy Policy Implementation. Initiative for Energy Justice. https://iejusa.org/justice-in-100-report/

Metrics will need to be relevant to the policy or design question at hand. The problems that will arise under a net zero system will require different metrics to account for environmental justice. For example, in the context of vehicle electrification, concerns include the extent of charging infrastructure in low-income and marginalized neighborhoods; vehicle adoption among marginalized segments of the population; and health co-benefits that arise from fewer fossil fuel vehicles in densely populated areas. In the case of enhanced geothermal systems, the metrics of concern will be different, including how the risks of induced seismicity impact different segments of the population.

One approach to assuring that the research community is measuring what matters is to use a version of community-engaged co-design to develop and verify equity metrics.[41] Value-focused thinking (VFT) is a method with rigorous underpinnings and potential for use with communities a range of other stakeholders.[42] VFT has been used to recently in Germany and Ghana to define strategic values and metrics for different stakeholder groups in the energy transition[43] and may be similarly useful for defining metrics for evaluating net zero systems. To be successful, such methods require close collaboration between the modelers or data scientists who are designing the metrics, energy systems experts, and representatives of marginalized communities.

3.2 The need to better understand inequities under the current energy system and the impact of existing policies and programs.

Second, we need evidence on what has and has not worked in the past. This means large scale empirical studies, using carefully developed metrics, evaluating policies and programs across locations and time. There exists work focused on distributional aspects of energy equity, including the distribution of risks[44] and of benefits.[45] Carley et al. recently inventoried and categorized energy justice programs across the US, identifying over 250 programs covering all states and with a wide diversity in approaches.[46] This is a critically important start; more work is needed to garner a fuller understanding of the equity impacts of regulations, programs, and policies. In particular, there is a need for more studies that address the procedural and

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[41] Blomkamp, E., 2018. The promise of co-design for public policy. *Australian Journal of Public Administration*, *77*(4), pp.729-743. Ambole, A., Musango, J.K., Buyana, K., Ogot, M., Anditi, C., Mwau, B., Kovacic, Z., Smit, S., Lwasa, S., Nsangi, G. and Sseviiri, H., 2019. Mediating household energy transitions through co-design in urban Kenya, Uganda and South Africa. *Energy Research & Social Science*, *55*, pp.208-217.

[42] Keeney, R.L., 1996. *Value-focused thinking*. Harvard University Press.

[43] Baker, E., Nock, D., Levin, T., Atarah, S.A., Afful-Dadzie, A., Dodoo-Arhin, D., Ndikumana, L., Shittu, E., Muchapondwa, E. and Sackey, C.V.H., 2021. Who is marginalized in energy justice? Amplifying community leader perspectives of energy transitions in Ghana. *Energy Research & Social Science*, *73*, p.101933; Höfer, T., von Nitzsch, R., & Madlener, R. (2020). Using Value-Focused Thinking and Multi-Criteria Group Decision-Making to Evaluate Energy Transition Alternatives. *Decision Analysis*. 17(4), 330-355.

[44] Cotton, M. Fair fracking? Ethics and environmental justice in United Kingdom shale gas policy and planning. *Local Environ.* (2017). 22, 185–202; Granqvist, H.; Grover, D. (2016). Distributive fairness in paying for clean energy infrastructure. *Ecol. Econ.* 126, 87–97.

[45] Zhou, S. and Noonan, D.S., (2019). Justice implications of clean energy policies and programs in the United States: A theoretical and empirical exploration. *Sustainability*, 11(3), p.807.

[46] Carley, S., Engle, C. and Konisky, D.M., (2021). An analysis of energy justice programs across the United States. *Energy Policy*, *152*, p.112219.

recognition aspects of policies, for example, by examining the impacts on the distribution of ownership and impacts on decision-making involvement of marginalized communities.[47]

3.3 The need to explicitly model equity outcomes in net zero systems.

Third, we need to ensure that prospective studies of net zero energy systems include energy equity. This is a particularly challenging task, since the distribution of income and other demographic variables in the far future is highly uncertain under both business-as-usual conditions and under different net zero scenarios. A key step is to derive meaningful equity metrics from models, especially large Integrated Assessment Models (IAM). Emmerling and Tavoni (2021) note that a number of IAMs have included income inequality, but future income distribution under even business-as-usual scenarios will be highly uncertain, and other aspects of equity, such as race, ethnicity or age, are lacking.[48]

A recent study provides an example of a multi-model framework for deriving equity metrics from IAMs. A study by Mercado Fernandez (2020) combines a detailed Generation and Transmission Expansion model and demographic data with the results from a model inter-comparison study to derive equity metrics around pollution, water-use, and pipeline development among low-income and indigenous people in Mexico.[49] Emmerling and Tavoni discuss other ways forward, including expanding scenario generation to include more aspects of inequality, in particular race; and to allow for dynamics between different types of agents, endogenizing interactions and outcomes.[50]

3.4 The need for marginalized groups at the table.

Fourth, and tying the above together, is the need to elevate the voices of people from marginalized and racialized communities, making sure these voices are part of research and analysis of net-zero energy systems.[51] This will require an intentional effort to increase demographic diversity and representation among researchers and analysts. Recent studies have revealed the persistence of implicit bias.[52] Groups lacking diversity tend to be echo chambers and miss out on the perspectives needed to ask new and important questions. There is more and more awareness of how to counter this trend;[53] energy systems researchers need to adopt these strategies and set clear objectives.

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[47] Verma, A. and Weststar, J., (2011). Token presence or substantive participation? A study of labor trustees on pension boards, *Management and Organizational Studies Publications*. 25. https://ir.lib.uwo.ca/mospub/25

[48] Emmerling, J. and Tavoni, M., (2021). Representing inequalities in integrated assessment modeling of climate change. *One Earth*, 4(2), pp.177-180.

[49] J. Veysey, C. Octaviano, K. Calvin, S. H. Martinez, A. Kitous, J. McFarland, and B. van der Zwaan, (2014). Pathways to Mexico's climate change mitigation targets: A multi-model analysis," *Energy Econ.*, vol. 56, pp. 587–599; Mercado Fernandez, R., (2020). Robust and Sustainable Energy Pathways to Reach Mexico's Climate Goals. PhD dissertation, University of Massachusetts, Amherst.

[50] Emmerling and Tavoni 2021.

[51] Jenkins, K.E., Stephens, J.C., Reames, T.G. and Hernández, D., (2020). Towards impactful energy justice research: Transforming the power of academic engagement. *Energy Research & Social Science*, 67, p.101510.

[52] Moss-Racusin, C.A., Dovidio, J.F., Brescoll, V.L., Graham, M.J. and Handelsman, J., (2012). Science faculty's subtle gender biases favor male students. *Proceedings of the National Academy of Sciences*, 109(41), pp.16474-16479; Williams, M.T., (2019). Adverse racial climates in academia: Conceptualization, interventions, and call to action. *New Ideas in Psychology*, 55, pp.58-67.

[53] Forscher, P.S., Mitamura, C., Dix, E.L., Cox, W.T. and Devine, P.G., (2017). Breaking the prejudice habit: Mechanisms, timecourse, and longevity. Journal of experimental social psychology, 72, pp.133-146; National

Beyond bringing in more diverse researchers, energy systems researchers can be more thoughtful about stakeholder engagement[54] and develop methods and research processes that allow for two-way knowledge exchange and equitable engagement with the communities they study.

4. Toward equitable and timely solutions

There are many possible pathways to mitigating climate impacts and many possible visions of a net zero energy system. In some cases, there may be trade-offs between economic efficiency and equity. For example, Wang et al. find a trade-off between carbon emissions and local pollution, particularly in the case of BECCS.[55] In other cases, there may be win-win solutions between climate change and other environmental justice related dimensions; Sergi et al. find that, for U.S. electricity decarbonization, considering climate change mitigation and air pollution reduction together provide larger net benefits to society than considering climate change alone.[56] However, there are other win-win solutions that may only become apparent through engagement and inclusion of marginalized and vulnerable communities in research design and implementation. Millward-Hopkins et al. note that it is *theoretically* possible (although politically challenging) to provide all people on Earth with decent living standards while reducing global final energy consumption by 60% in 2050.[57] We encourage the energy systems research community to include equity as a key objective when evaluating net zero scenarios, so that the inequities in today's energy system are not propagated through the energy transition.

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