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Algorithms for Energy Justice

Johanna L. Mathieu, University of Michigan, Ann Arbor, Michigan, USA

Abstract

According to the Initiative for Energy Justice, “Energy justice refers to the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those historically harmed by the energy system (“frontline communities”). Energy justice explicitly centers the concerns of marginalized communities and aims to make energy more accessible, affordable, and clean and democratically managed for all communities” [1]. Given this definition, energy justice clearly has social, economic, and health components; less explicit is the technological component that, at least in part, underlies our ability to make energy more accessible, affordable, and clean. Power system researchers do not often put our work into the context of energy justice. Energy justice papers are much more common in social science communities. However, I argue that power system engineers have a unique role to play in supporting and directly contributing to energy justice. Though given the techno-economic focus of our field, to make an impact, we must do this work in collaboration with social scientists, and ideally community-based stakeholders. In this chapter, I develop an energy justice research agenda for power systems researchers, define an example problem, and propose algorithmic approaches to solve it.

Keywords

Power systems; Energy justice; Energy transition; Energy equity; Distributed energy resources

1.0 Introduction

In response to climate change, the energy sector is going through a massive transition. In addition to decarbonizing the electricity sector by transitioning to renewable electricity sources, we are electrifying other sectors that have traditionally used fossil fuels, including the transportation sector, industrial sector, and the commercial/residential building sector that still uses fossil fuels for space and water heating, cooking, and so on.

Access to clean and affordable energy is inequitably distributed in our global society, both across countries and within countries. For example, low-income households and African-American households have the highest energy burdens in the U.S., where energy burden is defined as "the percent of household income that is spent on energy bills" [2]. The energy transition may exacerbate inequities unless we take a holistic approach that considers existing inequities; explores how inequities may change (improve or get worse) as a result of technological, economic, environmental, and social changes that will occur through the energy transition; and considers these factors in decision-making processes. As the International Institute for Sustainable Development explains, "Energy transitions are about people: the ones who make the decisions and the ones affected by those decisions. A 'just transition' approach ensures that the affected people are considered by those making decisions" [3]. The 'just transition' is related to the concept of environmental justice, which the U.S. Environmental Protection Agency (EPA) defines at "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation and enforcement of environmental laws, regulations and policies" [4].

In 2021, the Biden Administration issued an executive order establishing "a White House Environmental Justice Interagency Council … to prioritize environmental justice and ensure a whole-of-government approach to addressing current and historical environmental injustices, including strengthening environmental justice monitoring and enforcement…" [5]. It also created the "Justice40 Initiative with the goal of delivering 40 percent of the overall benefits of relevant federal investments to disadvantaged communities..." [5]. While focused broadly on environmental investments, the Justice40 Initiative also targets energy efficiency and clean energy investments [6]. For researchers in the U.S., a key impact of the Justice40 Initiative is increased federal funding for research projects that address the needs of underserved communities.

Regardless of the availability of funding, which undoubtably will ebb and flow with politics, power system researchers have an important role to play in the 'just transition.' The technologies that we design and develop have a direct or indirect impact on people's lives – through the cost of electricity, the frequency of power outages, the health impacts of fossil fuel plants, and so on. More homes have smart and connected devices that allow them to see their electricity consumption in real-time, and modify it. Distributed Energy Resources (DERs) in or at homes, like electric vehicles, flexible appliances, solar photovoltaics (PV), and battery energy storage, are taking a more active role in power system operations. However, these impacts and innovations affect different people differently. Minority households in Detroit, Michigan are disproportionally impacted by sulfur dioxide (SO_2) pollution from nearby power plants [7]. Increased adoption of solar PV by high-income homes can increase electricity costs for low-to-moderate (LMI) homes without solar PV [8] [9]. LMI households less able to afford the switch to electric heating, water heating, and clothes drying will be stuck paying for legacy gas infrastructure cost [10]. One might argue that historic and ongoing energy inequity that has led to these unequal energy outcomes stems from sources other than the technology itself – racism, classism, and so on – and so it is not the role of power systems researchers to right these wrongs. However, I would argue that through technology innovation we have levers to mitigate inequity. And if we can mitigate inequity, why wouldn't we?

Specifically, power systems researchers can directly contribute to 'energy justice.' Related to the concepts of environmental justice and the just transition, the Initiative for Energy Justice defines 'energy justice' as "the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those historically harmed by the energy system ("frontline communities"). Energy justice explicitly centers the concerns of marginalized communities and aims to make energy more accessible, affordable, and clean and democratically managed for all communities" [1]. Power system researchers do not often put our work into the context of energy justice. However, technology, at least in part, underlies our ability to make energy more accessible, affordable, and clean, and therefore can contribute to the goal of energy justice. Of course, technology alone will not mitigate all inequalities, and so, to make a significant impact, we must work in collaboration with social scientists, and ideally community-based stakeholders.

In this chapter, I begin with a discussion of key concepts within the field of energy justice and briefly review the broad literature in this field. I then connect the power systems literature to the field of energy justice, including linking work that has not been explicitly linked to the term "energy justice" before. Next, I describe a set of energy justice-related challenges that power system engineers are uniquely-positioned to tackle. Finally, I define an example problem and describe algorithmic approaches to address that problem, which my collaborators and I are currently developing and testing to improve energy access, affordability, and equity in LMI homes in Detroit, Michigan.

2.0 What is energy justice?

Energy justice is a concept that has appeared in the social science, engineering, economics, and policy literature. Sovacool and Dworkin's book on "Global Energy Justice" provides a broad overview of energy justice issues from the prospective of political theory [11]. Jenkins et al. provide a social science review and research agenda for energy justice, which they state should evaluate "(a) where injustices emerge, (b) which affected sections of society are ignored, (c) which processes exist for their remediation in order to (i) reveal, and (ii) reduce such injustices" [12]. Hernández argues for four energy-justice related rights, i.e., the right to 1) healthy sustainable energy production, 2) best available energy infrastructure, 3) affordable energy, and 4) uninterrupted energy service [13].

More technically-focused modeling and/or data analysis studies have tried to characterize energy inequity in terms of racial/ethnic and socioeconomic disparities, as a step toward rectifying those inequities and achieving energy justice. For example, Reames used data-driven models to explore disparities in heating energy use intensity (EUI), a metric used to characterize energy efficiency, in Kansas City, Missouri, and argued that an understanding of these disparities can facilitate targeting of energy efficiency interventions [14]. A latter study explored disparities in heating energy consumption and efficiency in Detroit, Michigan [15]. Both studies found significant correlations between heating efficiency and both racial/ethnic makeup and income, i.e., houses in areas with lower incomes and/or more racial/ethnic minority households had higher heating EUIs. Recently, Tong et al. used fine-scale spatial data from Tallahassee, Florida and St. Paul, Minnesota to explore these same relationships between EUI and income/race for both electricity and gas energy consumption, and obtained similar results [16]. They also found distinct income and racial effects [16]. Cong et al. explore hidden energy poverty through a data-driven approach that estimates energy-limiting behavior (e.g., delaying turning on air conditioning) in low-income households [17].

Other studies focus on the role of policy. In [18], Bednar and Reames argue that we should recognize energy poverty, defined as "the inability of a household to meet their energy needs" [18], as a distinct problem, different from general poverty, to enable a more effective response to energy poverty. They review existing US federal-funded energy programs that aim to reduce energy bills, and find that these programs' metrics are not well-aligned with the overall goal of reducing energy poverty.

Straddling social science, engineering, and policy, Baker et al. describe the challenges of and solutions to including qualitative understandings of stakeholder preferences within quantitative electricity system models used for sustainable and equitable electricity system planning [19]. This paper details some of the key challenges we, as power systems engineers, face in addressing energy justice in our own work – specifically, how do we bring energy justice concepts into our formulations as metrics, objectives, constraints, and costs?

3.0 Energy justice in power systems research

As of April 2022, an Institute of Electrical and Electronics Engineers (IEEE) Xplore search for "energy justice" brings up just three items: a conference panel abstract and two conference papers [20]-[22]. Kostyk et al. discussed the impact of energy justice on the energy transition on a panel at the 2011 IEEE International Symposium on Technology and Society [20]. More recently, [21] proposed an approach to explicitly include energy justice in the electrification planning process. The paper extends an agent-based planning approach introduced by [23] developed for electricity system planning in developing countries. Lastly, [22] studied residential solar adoption in Connecticut and shows that Connecticut's Residential Solar Investment Program (RSIP), designed to increase access to solar by LMI homes, has reduced racial and ethnic disparities in solar adoption. Arguably, [21] (and therefore [23]) is the closest to the field of power systems. Of course, not all power systems papers are IEEE publications. Nock et al. formulate a generation expansion planning model incorporating preferences for equity and budget, and discuss their findings in the context of energy access and energy poverty [24].

There is a significant body of power systems research that directly relates to energy justice even if the authors of that work have not explicitly connected their research to the term energy justice. Many papers published in the IEEE Power and Energy Society PowerAfrica Conference address electricity technology challenges and solutions for marginalized communities. For example, [25]-[27] describes the feasibility and challenges of renewable-energy-based microgrids in underserved communities in Africa. In an *IEEE Transactions on Sustainable Energy* article, Arriaga et al. explore a variety of scenarios for transitioning remote communities in Northern Ontario, Canada away from diesel to renewable energy resources [28]. In an *IEEE SmartGridComm* paper, Porter et al. design an algorithm to coordinate energy storage with diesel generation for a rural community in the Philippines and describe how prepaid electricity tariffs can be used to finance storage investment [29]. This list is not meant to be exhaustive (and I apologize to the authors of all the papers that have been missed), but is meant to demonstrate that power systems researchers already work on a variety of research problems with the goal of making energy more accessible, affordable, and/or clean for marginalized communities. I would argue that by explicitly linking our work to energy justice and putting energy justice goals front and center we can make even more impact in mitigating inequity.

A key linkage between power systems research and energy justice is the proliferation of DERs, which are a significant component of the energy transition. In Amory Lovins's seminal 1976 article "Energy Strategy: The Road not Taken?" [30], Lovins argues for the "soft" energy technologies – renewable, diverse, flexible, low-technology, and matched in scale and quality to end-user needs. Taylor et al. later linked this argument directly to the need for and benefits of DERs [31]. Lovins, the co-founder and former chief scientist of the Rocky Mountain Institute, argued against nuclear, coal, gas, and other "hard" energy technologies for a variety of environmental, political, and technical reasons, but also for society and equity. He explains, "Though neither glamorous nor militarily useful [referring to nuclear], these [soft] technologies are socially effective—especially in poor countries that need such scale, versatility and simplicity even more than we do" [30]. He goes on,

"The soft path has novel and important international implications. Just as improvements in end-use efficiency can be used at home (via innovative financing and neighborhood self-help schemes) to lessen first the disproportionate burden of energy waste on the poor, so can soft technologies and reduced pressure on oil markets especially benefit the poor abroad. Soft technologies are ideally suited for rural villagers and urban poor alike, directly helping the more than two billion people who have no electric outlet nor anything to plug into it but who need ways to heat, cook, light and pump. Soft technologies do not carry with them inappropriate cultural patterns or values; they capitalize on poor countries' most abundant resources (including such protein-poor plants as cassava, eminently suited to making fuel alcohols), helping to redress the severe energy imbalance between temperate and tropical regions; they can often be made locally from local materials and do not require a technical elite to maintain them; they resist technological dependence and commercial monopoly; they conform to modern concepts of agriculturally based eco-development from the bottom up, particularly in the rural villages." [30]

Laying out a roadmap for "Power Systems without Fuel," power systems researchers Taylor et al. discuss the fundamental challenges and power systems research opportunities associated with the transition to 100% renewable power systems [31]. However, they do not link back to Lovins argument about the role of "soft" energy technologies/DERs[1] in mitigating inequities and therefore advancing energy justice. If we do make this link, it opens up a wide array of research questions that we, as power systems researchers, are uniquely positioned to tackle, as I will describe next.

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[1] Albeit, not all "soft" energy technologies are DERs, and vice versa.

4.0 An energy justice research agenda for power systems researchers

Many of the papers described in the previous sections directly or indirectly relate to power systems research. I next attempt to organize these ideas into a list of power systems research topics in order to create an energy justice research agenda for power systems researchers. Given the definition of energy justice above, all work we do to increase the affordability of electrical energy (which can increase access) and/or enable a cleaner energy system (e.g., through renewables) is nominally related to energy justice; however, here I focus on problems that place energy justice objectives front and center. I note that this list is not comprehensive.

4.1 Equitable electricity system planning

Arguably the most straightforward way of integrating energy justice into power systems research is within electricity systems planning, i.e., planning of new/expanded generation, transmission systems, distribution systems, and demand-side management programs. Several of the studies mentioned above have proposed electricity system planning paradigms that include energy justice objectives, both for planning to increase access in developing countries and planning to mitigate historic inequities in countries with more advanced electricity infrastructure. Electricity planning studies often involve simulation modeling and/or formulating and solving optimization problems. Key research questions include how to define quantitative energy justice metrics that can be used to evaluate simulation outcomes and/or can be embedded within optimization formulations. For example, how do we define the "cost" of unequal electricity reliability or unequal health impacts due to fuel extraction, processing, and use, or should we include constraints to enforce more equitable solutions? Do the answers to these questions differ when we consider traditional grid development and expansion (large-scale conventional power plants, transmission) versus the development and deployment of DERs (which people interact with much more directly)? How will the distributional impacts of power systems change throughout the energy transition, and how can we steer the transition to achieve energy justice?

4.2 Equitable electricity system operation and control

Beyond planning to improve equity, can we operate and control existing grids in ways that promote equity? The usual goal of security-constrained economic dispatch is to achieve lowest-cost power plant dispatch that meets the grid technical and reliability constraints. How can we embed energy justice metrics within this optimization problem, for example, by penalizing spatially unequal reliability and pollutant emissions outcomes? How can we design power system controls to achieve more equitable outcomes, for example, by ensuring that emergency load shedding does not always affect the same neighborhoods? The energy transition will lead to the need for fundamentally different approaches to operate and control grids dominated by highly-distributed inverter-interfaced energy resources [31]; how do we embed energy equity objectives within these approaches?

4.3 Equitable DER adoption and coordination

Digging a little deeper into the last point, we expect DER coordination to be a key element of future low-carbon power grids. Residential DERs, like flexible appliances, battery energy storage, electric vehicles, and rooftop solar, can be coordinated to help balance renewable/load variability and also manage grid constraints. However, LMI households are less able to afford the upfront costs of DERs and therefore will be later to benefit from these technologies, while at the same time shouldering more and more of the cost of legacy energy infrastructure.

LMI households that adopt DERs may also find that their DERs are unequally coordinated. There are a variety of approaches to coordinate DERs including price-based control, market-based control (e.g., transactive energy), and direct control by a utility or third-party aggregator, which generally involves establishing a contract detailing the flexibility and compensation. If prices/markets drive coordination decisions, LMI households are more likely to shoulder a great burden of coordination, for example, they may be more likely to shift appliance load and vehicle charging to inconvenient times to obtain lower electricity rates, and/or to reduce heating/air conditioning to uncomfortable temperatures to reduce electricity costs during high-price hours. While these types of actions are exactly what DER coordination tries to achieve, unequal energy burdens mean LMI homes will have far more to lose if they make decisions inconsistent with economic signals. Even direct control does not necessarily solve this problem; LMI homes participating in direct control may choose to offer more flexibility to the utility or aggregator than higher-income homes to achieve higher compensation (lower electricity rates and/or higher participation incentives), which could make their homes less comfortable.

Therefore, power systems researchers have a variety of research questions to address. First, with respect to adoption, how can we increase equitable adoption, for example, through the design of innovative business models linking DER adoption and coordination for LMI households? While designing “business models” may not seem like the task of a power systems researcher, in this case the “business model” is inherently linked with the coordination strategy (i.e., an optimization and/or control-based approach tailored to the physical capabilities and constraints of the DERs and the grid) and so this research question is well-aligned with power systems research. An example model is one in which an aggregator owns/operates DERs within homes, delivering contracted services (renewable power, heating, cooling, etc.) to the homes for a fee, while coordinating the DERs to provide grid services, in turn providing income to the aggregator, some of which is passed on the homeowner. The economics of this model – both whether this is profitable to the aggregator and appealing to LMI homeowners – are a function of the ability of the aggregator to provide reliable grid services with the DERs, which is a power systems research topic. A second research question is how to design DER coordination algorithms that do not place additional burdens on LMI households. Can DER coordination also serve to mitigate *existing* inequality, for example, by *increasing* the comfort of LMI households?

4.4 Equitable electricity rate and demand-side management program design

As mentioned above, LMI households will end up paying more for electricity to cover grid costs as higher-income homes adopt solar PV. This is due to how most existing electricity rates are structured, with fixed kWh charges that cover both energy (fuel) costs and network fees. As homes with solar PV consume less kWh, they will pay for less energy and also a lower portion of the network fees, though their network connection will still support essentially the same level of reliability. This may increase kWh costs, which will lead to higher energy burden for LMI households without solar PV. We could adapt electricity rates to this new reality, for example, by having homes with solar pay a separate network charge. This is highly controversial as it is seen as a “tax” on solar PV, discouraging homes from investing in renewables.

Clearly, we need new rate designs, but how do we do this in fair and effective ways? Rate design is a topic often explored by economists, for example, [32] explored how electricity rates in California should change to ensure equity through the energy transition. However, power systems researchers also have a role to play in rate design, since rate designs affect electricity consumption patterns, which directly affect the operation of power grids. Research questions include how proposed "equitable" rates affect consumption, and in turn operations and control, and subsequently grid costs, reliability across space and time, and health impacts across populations. Can we design equitable rates through formulations that specifically consider these dependencies, for example, via bilevel optimization problems that optimize power system operation including cost, reliability, and equity objectives subject to the optimization problem of electricity consumers? If we agree that a basic level of electricity access is a human right [33], how can we design electricity rates to provide that level for free or very low cost while ensuring sufficient cost recovery for the utility and dynamic stability?

Beyond rates, power systems researchers can also contribute to the design of demand-side management programs that also affect electricity consumption patterns. Energy assistance programs enable LMI homes to make home/appliance upgrades and provide a variety of other energy-related support. For example, the US government's Low Income Home Energy Assistance Program (LIHEAP) "assists eligible low-income households with their heating and cooling energy costs, bill payment assistance, energy crisis assistance, weatherization and energy-related home repairs" [34]. As [18] explains, assistance program metrics are not always aligned with overall programmatic goals to reduce energy poverty and achieve energy justice. Energy efficiency programs are more broadly accessible to the population and aim to reduce energy consumption. Demand response programs aim to achieve load flexibility by incentivizing demand shedding or shifting at key times to reduce peak load, manage whole electricity price volatility, improve grid reliability, help manage renewable energy generation intermittency, and so on. All three types of programs need to evolve to drive toward energy justice and enable the energy transition. How can we redesign energy assistance program metrics to better align with overall programmatic goals? How can we restructure energy efficiency programs to reach the homes that can benefit the most, i.e., those that suffer the highest energy burden? How should we consider energy justice goals within demand response programs, which traditionally do not consider equity or justice goals at all? While broad, these research questions must be tackled by researchers in energy policy, economics, and power systems, ideally working in collaboration with one another.

4.5 Recommender systems for electricity rates and demand-side management programs

In addition to designing new electricity rates and demand-side management programs, we also need to develop better ways to link homeowners with the programs that best suit their needs. “Recommender systems” have been popularized through web and social media applications, for example, the Netflix Prize Competition [35]. However, “recommender systems” can also be used for energy applications. Designing a recommender system to recommend electricity rates and/or demand-side management programs to LMI households requires not only expertise in the machine learning approaches that underpin the algorithms, but also expertise in power systems research. More details are provided in the next section.

4.6 Reducing bias in data-driven algorithms for power systems

In mentioning recommender systems, I would be remiss if I did not also discuss bias in machine learning and artificial intelligence (AI) systems. The National Renewable Energy Laboratory recently held a Workshop on Responsibly and Trustworthy AI in Clean Energy with the goal of “establish[ing] practices, principles, and behaviors needed for responsible and trustworthy AI for clean energy” [36]. More and more power systems research is leveraging emerging tools from machine learning and AI to solve power systems challenges in data-driven ways; however, we need to be aware that these tools and techniques can be biased, which can lead to the perpetuation of inequities. Can we characterize the bias inherent in these tools and understand how it would impact the use of machine learning and AI in power systems applications? How can we redesign these tools to mitigate bias in our applications?

5.0 Example problem and algorithmic approaches

This section describes an example problem that we, as power systems researchers, are well-positioned to tackle. I describe the inherent challenges to solving this problem and some proposed algorithmic solutions to the problem. I also highlight open problems.

5.1 Problem: How can we more effectively recommend energy assistance, energy efficiency, and electricity rate programs to LMI homes?

As part of an U.S. National Science Foundation Smart and Connected Communities project, my collaborators and I are currently developing data-driven algorithms to increase energy access, affordability, and equity in LMI households in Detroit, Michigan. In collaboration with researchers in power systems, energy justice, public health, and survey research, along with several community-based organizations, the team is conducting an intervention in 100 LMI households to explore the effectiveness of *energy case managers* in improving access to energy assistance, energy efficiency, and electricity rate programs, and in turn reducing energy burdens and/or improving comfort in these LMI households. The energy case managers will use household data, including survey data, smart meter data, and submetering data (when available) to develop energy improvement plans and make recommendations for programs.

Available energy data can be leveraged to determine whether households qualify for specific programs and whether they would benefit from participation in programs. To qualify for energy assistance programs, a homeowner usually needs to prove their LMI status. Some energy efficiency and rate programs also have qualification requirements that depend on income or other factors. How much households would benefit from these programs – in terms of monetary savings and/or increased comfort – depends upon how the household currently consumes electricity and how the program will change their energy consumption patterns. It also depends on their electricity rate. One method of estimating these benefits is by modeling the household's electricity consumption, leveraging available household data to parameterize the models. Then, one can simulate how the household's electricity consumption would change if the house were weatherized, old appliances were replaced, and so on. To determine the best electricity rate, one could run historic consumption data through alternate rate structures to determine whether homes would save money simply by switching to another rate. Different rates can also induce behavior change, for example, time of use rates encourage households to shift consumption to off-peak hours. To estimate the benefits of a new rate plus behavioral change, one can again use models to simulate how the household's electricity consumption would change.

5.2 Challenges

Developing accurate models of household electricity consumption and human behavior is nontrivial. To capture the impact of weatherization (which affects heating and cooling energy consumption), appliance replacements, and behavioral change affecting the usage of specific appliances, we need to model the major loads within the home. Moreover, while modeling the *impact* of behavioral change on electricity consumption (e.g., the impact of a homeowner shifting clothes drying from 6pm to 10pm) is difficult, modeling the behavioral change itself (e.g., the new clothes drying time, here assumed to be 10pm) is much much harder.

5.3 Algorithmic solutions

1) Modeling loads within a home

Most homes in the U.S. now have smart meters that record data hourly or half-hourly. How do we go from this data to household-specific models of all of the major electric loads within a house? A first step could be to use Non-Intrusive Load Modeling (NILM), also referred to as Energy Disaggregation, to disaggregate time-series home-level electric load data into estimates of time-series individual electric load data [37]. More formally, NILM takes in a time-series of smart meter measurements s and uses a supervised or unsupervised learning algorithm f to output a set of time series Y representing the consumption of a particular household's electric loads, i.e., $Y = f(s)$. Additional data, such as partial submetering data from one or multiple household loads Z, can also be leveraged, i.e., $Y = f(s, Z)$. NILM is not a new field – the problem was first posed in the early 1990s [38] – and many papers exist with different methods and case studies; however, a key open problem is how well existing NILM methods can disaggregate data from LMI households or households of racial/ethnic minorities, which may have different load consumption patterns than other households. NILM methods generally require training on real data, ideally from the household in question, or at least on data from similar households. However, there is a dearth of publicly-available data from diverse households in the US. Pecan Street Inc., which provides Dataport [39], a massive database with high resolution submetering data from homes in multiple states, has little data from LMI household data. Our team is working with Pecan Street Inc. to add submetering to 75 owner-occupied LMI households in two Detroit neighborhoods with predominantly Black and Hispanic populations.

Once appliance consumption is estimated, it can be used to fit the parameters $a \in R^n$ of physics-based load models g, for example, air conditioning models that capture how their power consumption p depends on their on/off mode m and temperature θ dynamics, i.e., $p = g(m, \theta, a)$ where $m \in \{0,1\}$ [40], [41]. However, using messy real-world data for load parameter identification is difficult. While we would like to identify the parameters of a model that captures the salient physical processes, we may struggle to measure all desirable states and the parameters may not be identifiable from the available measurements. A key open problem is how to determine the model complexity that presents the best tradeoffs between simplicity and accuracy in predicting the electricity consumption impacts of changes in appliance efficiency or usage.

2) Modeling behavioral change

While modeling behavior itself is more-or-less out of our purview as power systems researchers (though some of our colleagues do work on this), we do routinely model optimal decision making. Of course, people are not rational decision makers and so it is insufficient to model behavior as the outcome of an optimization problem. However, behavioral choices that can be automated, such as appliance settings, can be informed by optimization models. The results of these optimization models can be presented to householders together with program/rate recommendations, for example, "If you switch to x rate you will save y, and if you optimally schedule your appliances/thermostats, you will save z." The generic optimization problem can be formulated as minimize $h(x)$ subject to $q(x) = 0,\ r(x) \leq 0$, where x are the decisions, e.g., appliance and thermostat settings, battery and/or vehicle charging schedules, and so on. The function $h(x)$ encodes the "costs" including the cost of electricity and the (negative) benefit of home comfort and conveniences. The constraints $q(x) = 0,\ r(x) \leq 0$ encode the equality and inequality constraints, respectively, around load usage needs and physical load capabilities/constraints. There are a large number of papers focused on formulating and solving such decision-making problems to schedule and control residential electric loads, energy storage, and solar PV systems. Commercial Home Energy Management Systems (HEMS) can already be used to schedule smart appliances and thermostats to reduce energy costs. But a key open problem is whether existing approaches accommodate the diverse needs of LMI households or households of racial/ethnic minorities, such that the outputs of these optimization problems are actually useful to diverse homes. Moreover, how can we embed energy justice-promoting costs and constraints into these formulations?

6.0 Conclusions

This chapter detailed the intersection of energy justice and power systems research. I described a set of energy justice-related challenges that power system engineers are uniquely positioned to tackle, along with an example problem and some proposed algorithmic approaches to address it. My goal was to link together some seemingly disparate but inherently interlinked literature in order to make the case that power systems researchers can and should contribute directly to energy justice within their own work. The energy transition is not straightforward – there are enumerable paths we could take – but one that centers energy justice together with the need to combat climate change will lead to better distributional outcomes and a better chance of an overall equitable, fair, and stable solution.

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Author Biography

Johanna Mathieu is an Associate Professor of Electrical Engineering and Computer Science at the University of Michigan Ann Arbor. Her research focuses on ways to reduce the environmental impact, cost, and inefficiency of electric power systems via new operational and control strategies. In particular, much of her work develops new methods to actively engage distributed energy resources such as energy storage, flexible electric loads, and distributed renewable resources in power system operation. This is especially important in power systems with high penetrations of intermittent renewable energy sources such as wind and solar. She uses methods from a variety of fields including control systems and optimization.

Mathieu received her SB from MIT in Ocean Engineering with a minor in Ancient and Medieval Studies in 2004. She had always loved math but was also intrigued by archaeology, and decided to declare ocean engineering as her major as the result of a field trip to the Woods Hole Oceanographic Institution (WHOI) during her freshman year at college. There she learned about underwater archaeology and how WHOI researchers were developing underwater robots for underwater archaeological site exploration and mapping. In her senior year, she learned about another side of ocean engineering – wave energy harvesting for electricity generation. Her senior design project was to develop a wave energy harvester that she and her team built and deployed in the Charles River, her first foray into renewable energy technologies.

Burnt out after four years at MIT and wanting to do something that made a direct impact on people's lives, Mathieu joined the US Peace Corps after college and spent a year in Tanzania teaching high school math and physics. In 2006 she started her MS/PhD at the University of California, Berkeley in Mechanical Engineering without a clear plan for what exactly she planned to do, though with a declared focus in control systems. She had hoped to marry her interest in engineering with her experiences working in a developing country, and so took a class called "Design for Sustainable Communities" which led to her MS research with Prof Ashok Gadgil on arsenic remediation of drinking water for Bangladesh. She traveled to Bangladesh several times to test the technology and build prototypes. However, she found herself doing more chemistry than math, and no control systems at all.

Working with Prof Gadgil, Mathieu was an affiliate at Lawrence Berkeley National Laboratory (LBNL), and so she started attending more seminars and meetings there with researchers working on building efficiency and demand response. She volunteered to help with some projects within the LBNL Demand Response Research Center and also started working with Prof Duncan Callaway who had recently joined Berkeley within the Energy and Resources Group. The work was an ideal match of math-heavy engineering with social impact; she had found her calling. Her PhD research focused on demand response – both characterizing commercial building response to demand response signals, and developing control system approaches to coordinate residential load participation in grid ancillary services.

In the final year of her PhD, Mathieu was unsure if she should pursue a career in a national laboratory or academia. She had collaborated on a project with a visiting student from ETH Zurich, and was intrigued by the research coming out of his group. With advice from a trusted mentor Sila Kiliccote, then at LBNL, that Europe was the place one should go if one really wanted to learn about cutting edge grid/renewable energy technologies, she reached out to Prof Göran Andersson at ETH Zurich and was offered a postdoc. She spent a year and a half in Zurich working for Prof Andersson contributing to a number of research projects related to energy storage and stochastic optimal power flow, and also learning how to mentor PhD students.

In January 2014 Mathieu started as an assistant professor at the University of Michigan. She is still continuing research related to her PhD and postdoc but has broadened her research to also work on topics such as coordination of coupled infrastructure networks, learning-based approaches to disaggregate feeder load, and characterizing the environmental impacts of storage. Now, post-tenure, she is also pivoting back to some of the fields that she was once passionate about, in particular, developing technologies for marginalized communities. She currently has an NSF Smart and Connected Communities project to develop data-driven approaches to increase access to energy assistance, efficiency, and rate programs by LMI households in Detroit, MI.

Mathieu is the recipient of a 2019 NSF CAREER Award, the Ernest and Bettine Kuh Distinguished Faculty Award, and the U-M Henry Russel Award. She was a speaker at the 2021 National Academy of Engineering US Frontiers of Engineering Symposium. Mathieu is a Senior Member of the IEEE and currently serves as the Chair of the IEEE Power and Energy Society Technical Committee on Smart Buildings, Loads, and Customer Systems.