MY AWESOME PRELIM TITLE

BY

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PRELIMINARY EXAMINATION

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Abstract

This is a comprehensive study of caffeine consumption by graduate students at the University of Illinois who are in the very final stages of completing their doctoral degrees. A study group of six hundred doctoral students. . . .

This thesis is dedicated to my parents, and to my 17 year-old self who would have never believed it possible.

Acknowledgments

People to acknowledge

- Denia Djokić
- Shannon Anderson

Table of contents

List of Abbreviations

IPCC International Panel on Climate Change 2

Chapter 1

Motivation and Introduction

Chapter 2

Literature Review

Every year, world leaders meet to discuss plans to address climate change at the COP summit (cite). In 1995, world leaders established a set of targets with the Kyoto Protocol (cite) and again with the 2016 Paris Climate Agreement. Every few years, the United Nations releases a report from the International Panel on Climate Change (IPCC) assessing the current impacts of climate change and forecasting future scenarios. It seems that most of the world understands that anthropogenic climate change is an existential threat to society. Indeed, many studies in the energy system optimization model (ESOM) literature begin with a statement about the urgency of climate change. This chapter reviews the extant literature for both quantitative and qualitative analyses of the problem considered in this thesis – primarily bridging the gap between feasibility or planning studies to address the climate crisis and the current pattern of missed targets and growing carbon emissions. First, I draw from the risk assessment literature to characterize and situate the problem of climate change and demonstrate the necessity of a holistic analysis. Second, I build upon the central issue of disproportionality of climate change risk by reviewing the energy and environmental justice literature. Third, I develop an encompassing definition of an "energy system" using technical and social perspectives. Finally, I review the energy system literature for gaps in conventional modeling practices and identify previous attempts to incorporate social science and justice concepts into energy system models.

2.1 Characterizing the Problem of Climate Change

Risk is generally understood as the "potential for adverse consequences" [1]. However, due to the complexity of climate change, the IPCC developed a three-tenet framework to discuss risk [1]: hazard, exposure, and vulnerability. *Hazards* are mediated by physical features, such as climate and topography [2], [3]. Climate change is already producing stronger hazards, like forest fires, hurricanes, storms, floods, droughts, and heat waves [4]–[6]. *Exposure* refers to the scale and duration of the subjection of people, infrastructure, and social wealth to a particular hazard [1], [3], [7]. *Vulnerability* is the ability of a system to cope, recover, and adapt after exposure to a hazard. Although climate change is a worldwide phenomenon, vulnerabilities to its hazards are not uniformly distributed. On the contrary, the people and communities most likely to be harmed by climate change are those already being harmed by social inequities [8]. Recent work from Simpson et al. [3] expanded on this definition of risk by including *responses* to risk as itself a driver of risk. This framework is illustrated in Figure 2.1 Considering the actions taken (or not) in response to climate change is important for a holistic understanding of risk because it encompasses benefits and mitigating outcomes,

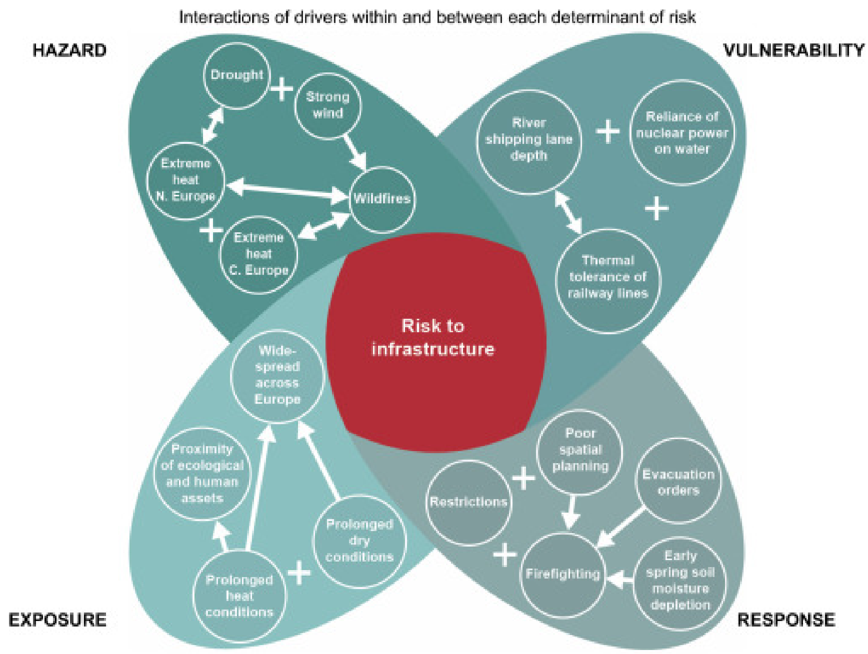

Figure 2.1: A framework for decomposing risk into its parts: hazard, exposure, vulnerability, and response, using risk to infrastructure as an illustrative example. Reproduced from Simpson et al. (2021) [3].

not just negative, inflammatory ones. Additionally, various stakeholders perceive the costs and benefits of (in)action differently, and therefore, including response as a driver of risk is essential for making choices more transparent and actionable within decision-making structures [3]. Responses to climate change risk come in myriad forms, and at multiple scales, from individual choices (e.g. demand response) [9]–[11], to communities [12], [13], and at the national level [14], [15]. Paterson and Charles [12] developed a descriptive typology for community-based hazard responses that also applies to national and global scales. The five response categories making up this typology are: [12]

1. individual and material well-being, which seek to meet individuals' basic needs such as food, water, shelter; and also livelihood, and health.
2. relational well-being emphasizes community and support networks and could include evacuation or relocation.
3. awareness involves monitoring and stock-taking of potential hazards.
4. governance relates to decision-making structures around human-hazard interactions.
5. infrastructure refers to the physical defense against hazards using engineered tools or ecological characteristics.

Figure 2.2 shows the breakdown of the categories. Although this framework is also useful for assessing policies to mitigate climate change, these response categories are related to specific climatic hazards rather than climate change mitigation.

Based on the net-zero carbon emissions target set by the 2015 Paris Agreement, thousands of countries, states, and companies have set climate policies covering two-thirds of the global economy [16]. Reducing CO_2

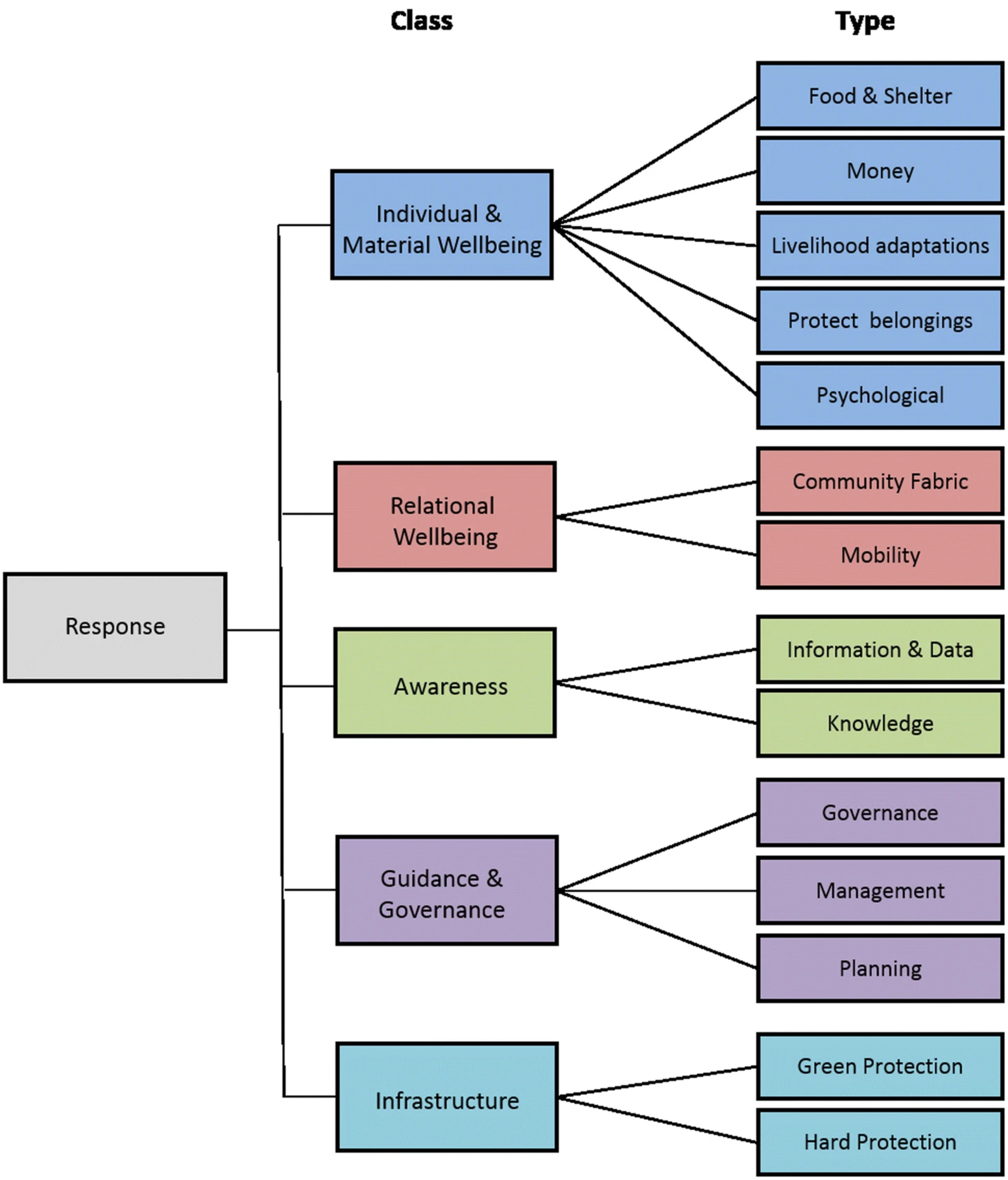

Figure 2.2: A categorization schema for various responses to climate risks. Reproduced from Paterson et al. (2019) [12].

(or CO_{2eq} in some cases) emissions is the primary focus for most of these policies [14]–[16], which includes the following broad strategies [15]:

1. Reducing greenhouse gas (GHG) emissions by transitioning from fossil-fueled to clean energy.

2. Removing CO_2 from the atmosphere using carbon-capture and storage (CCS) and other sequestration techniques.

3. Altering the Earth's energy balance by increasing its albedo and other geoengineering concepts.

In spite of this, only around five percent of these policies are considered robust according to their consistency with the United Nations (UN) "Race to Zero" campaign [16]. Further, even the full implementation of national climate policies leaves approximately a 28 $GtCO_{2eq}$ gap in GHG emissions [14]. This gap, as well as the fundamental assumptions about carbon sequestration from the 2015 Paris Agreement, suggests that the world is on track to overshoot these emissions targets [14], [17]. Carley et al. (2018) developed a quantitative framework for assessing the vulnerabilities associated with energy policies, or responses [18].

Risk analysis is the first step to a complete understanding of the climate crisis. The literature on disproportionality further distinguishes *risks* and *impacts* [2]. Consistent with previous work, a risk is the aggregate of hazards, exposures, vulnerabilities, and responses. Impacts, then, are the realizations of risk in terms of loss and damages. This distinction is essential. Responses to *impacts* are always done *ex post facto*. Differences in vulnerability to a hazard, often arbitrated by socio-economic status, manifest as differential impacts. Access to resources conditions an individual's or community's ability to respond to the impacts of a hazard. Since losses from impacts disproportionately affect those with the fewest resources, their vulnerability to future hazards increases in a "vicious cycle" [2], [8]. In purely economic terms, the loss of ecosystem services from land use change associated with climate change and other human activities is estimated at $4 - $20 trillion per year (in 2011 $US), globally, [19] and the poorest third of U.S. counties will experience financial damages between 2 and 20 percent of their annual income [20]. However, impacts also have cultural and psychological dimensions [2] that cannot be captured by accounting for "externalities."

Dorkenoo et al. [2] establish *burdens*, injustices arising from imbalances in social, political, or economic power, as a third theme that is paramount for a holistic understanding of disproportionality. Burdens influence all aspects of risk and affect access to resources which condition impacts. Dorkenoo et al. wrote, "[p]rocesses of marginalization and exclusion influenced by power struggles [...] influence the distribution of burdens and consequently responsibilities, in addition to the different dimensions of climate risk (hazard, exposure, vulnerability [, response])" [2]. Figure 2.3 demonstrates the mutually reinforcing relationships among risks, impacts, and burdens. A particularly relevant example of burden is the persistence of energy burden, where low-income households pay the highest percentage of their income on energy bills, relative to other income groups [21], [22]. Energy burden interferes with electricity access, thereby increasing vulnerability to extreme heat events [22], [23]. The risk assessment literature, as well as the energy system modeling literature, typically adopt an apolitical framing of vulnerabilities. However, inequities do not arise in a vacuum but through processes of marginalization and exclusion [24]. Often the distribution of burdens falls along class, race, and gendered lines [24], [25]. Research on siting patterns of polluting facilities indicates these projects frequently developed in areas with people of color and low-income populations [25]. Pollution from these facilities creates additional burdens for nearby communities. The energy and environmental justice literature offer insights to contrast this neutral framing and facilitate normative questions about alternative distributions [2], [24].

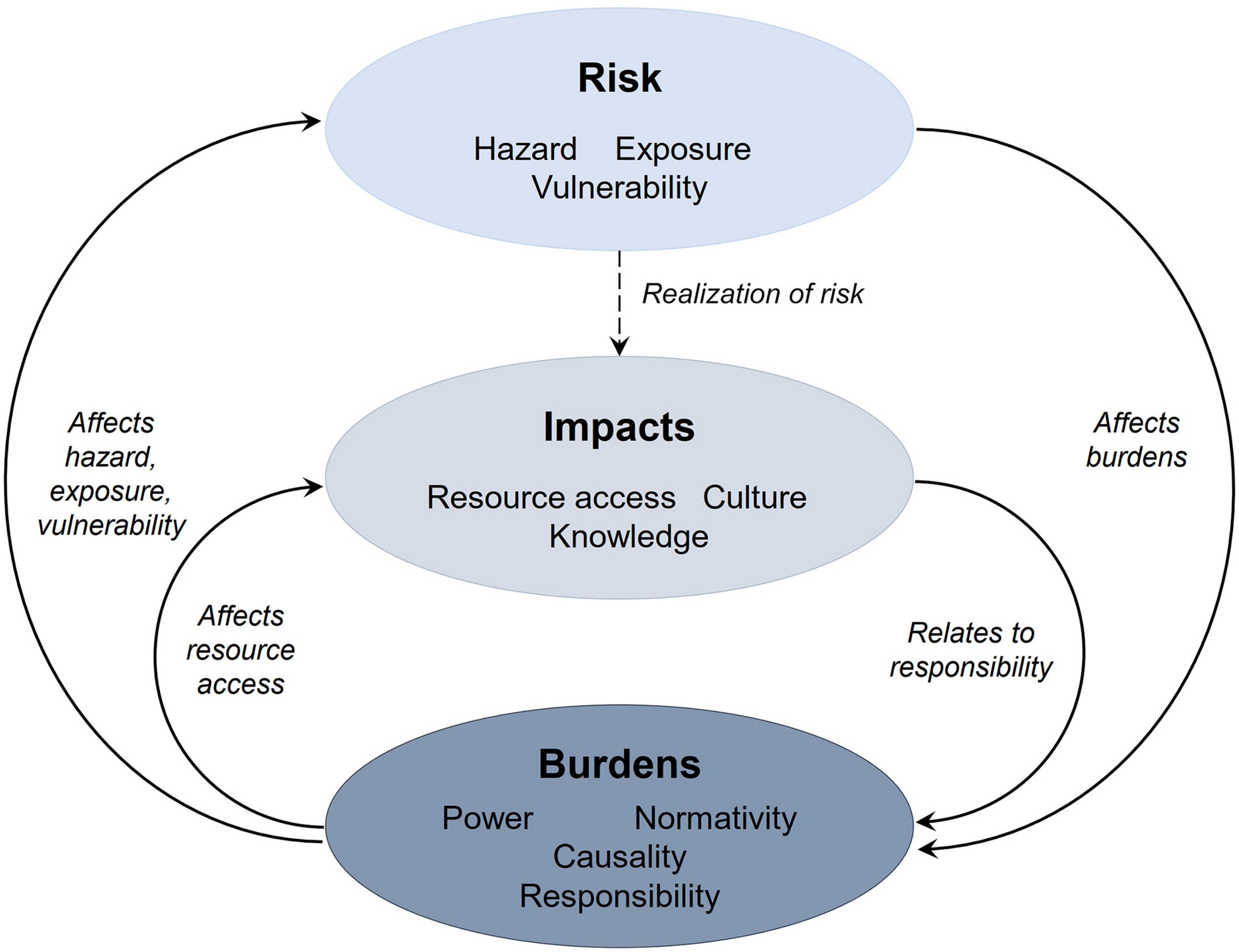

Figure 2.3: The relationships among risks, impacts, and burdens. Reproduced from Dorkenoo et al. (2022) [2].

2.2 Climate and Energy Systems

Climate change is driven by GHGs, a significant byproduct of the infrastructure that creates, delivers, and consumes energy (i.e. energy infrastructure). Specifically, due to the fraction of carbon emissions already coming from electricity generation (25 percent in the United States [26]) and the full decarbonization of the global economy requiring electrification of other sectors such as transportation and heat, thereby increasing the demand for electricity, even when accounting for efficiency improvements [27], [28], decarbonizing our electricity production is one of the most important issues to resolve climate change. Therefore, producing electricity with zero GHGs will initiate a cascade of deeper decarbonization throughout the economy but will require expanded electrical infrastructure. Accelerating the adoption of clean energy technology is essential for achieving a stable climate [14], [17].

2.2.1 Technical Solutions to Energy Decarbonization

Many studies show that global and local economies can be supported by 100% variable renewable energy (VRE), such as wind, hydro, and solar power [29]–[41]. Yet some countries that transition to majority VRE observe greater carbon emissions or a slower-than-expected reduction due to greater dependence on natural gas [42]. Other studies demonstrate that nuclear power is necessary for the deep decarbonization of our energy systems [42]–[52]. While some countries are building new nuclear reactors and the Nuclear Regulatory Commission (NRC) just approved the first small modular reactor design from NuScale [53], other places are shutting down their operating nuclear plants [54]. In the latter cases, places that shut down nuclear plants always saw a subsequent rise in carbon emissions, due to greater dependence on natural gas. Show plot of carbon emissions vs time for New York?. Further, the only examples of highly decarbonized electrical grids are places with a high penetration of hydro or nuclear power, and the former is widely considered exhausted. There is nearly universal agreement that decarbonizing electricity requires phasing out fossil-fueled power plants and a significant expansion of clean electricity generators. Although many studies show the *feasibility* for a variety of energy mixes, the following is strongly debated in the literature.

1. Whether energy systems should be 100% renewable or nuclear power and CCS should be included [13], [31], [49], [55].
2. What the role of distributed and decentralized energy sources in expanding our energy infrastructure should be [10], [56]–[62].

The strength of the technical arguments on both sides of these discussions combined with the distinct lack of sufficient policy agendas pursuing any of them [14], [16], suggests the existence of poorly articulated trade-offs and that technical solutions cannot be assessed from an engineering perspective, alone. Some researchers and policymakers disagree on technical grounds, while others disagree on the basis of institutional or systemic injustices. There are also differences in values. Clean technologies like nuclear power and renewables, such as solar or wind power, are not only different in how they produce electricity but also in the values and paradigms they represent. Sometimes, communication fails because the question being discussed is not agreed upon either. Often, feasibility studies address the positivist question, "what is the least-cost pathway to the energy transition," while others consider more normative questions, such as "how should we proceed equitably?" Normative questions are qualitative and, therefore, inherently challenging to answer and require the application of ethics. Indeed there are many more normative questions than positive ones. Is perfect the enemy of good? How do we balance stakeholder preferences, upstream and downstream effects, and the necessity to respond quickly to climate change? Will this mix of influences lead to paralysis or inaction? Given climate change's complex, interacting, and disproportionate nature, engineering alone is ill-equipped to resolve the problem. Ideas from the environmental and energy justice literature offer a social perspective for addressing the risks and impacts of climate change hazards.

2.2.2 Energy Justice

Energy justice is a conceptual and analytical tool regarding the ethical or normative dimensions of energy systems and addresses the systemic causes of burdens, and inequities [63].

There are many conceptions of justice; however, the most popular framework for understanding justice is a three-faceted approach originating from David Schlosberg: distributional, recognitional, and procedural justice [64]. Distributional justice relates to the fair distribution of resources, burdens, and responsibilities. Studies on distributional justice seek to address the normative question: how should a just society distribute the benefits it produces and *the burdens required to maintain it* [65]. Additionally, distributional justice considers *how* poor distributions are created [64]. Procedural (in)justice is defined as the presence of (un)fair and (in)equitable institutional processes of the state [64]. In other words, how decisions of societal import are made and who is involved in those decisions. Sovacool and Dworkin (2015) outline four elements of procedural justice: transparency, meaningful participation, impartiality, and avenues for redress [63]. Justice of recognition is the vaguest of the three tenets of justice and is frequently reduced to a component of either distribution or procedural justice [64], [66]. A common argument for this consolidation is that recognition is a precondition for achieving distributional justice or that achieving procedural justice necessarily includes recognition [64]. However, recognition is unique from distributive and procedural justices because it is concerned with a different family of injustice, namely, *misrecognition* [66]. van Uffelen (2022) suggests a nuanced definition of recognition justice as "the adequate recognition of all actors through love, law, and the status order" [66]. Sovacool and Dworkin (2015) offer a framework for assessing energy policies from a justice perspective. Table 2.1 map the relationships between justice-as-a-decision-making-tool from Sovacool & Dworkin, Paterson's hazard response characterization, and Schlosberg's triumvirate of justice.

Table 2.1: Different ways to operationalize justice concepts.

Schlosberg [64]	Sovacool & Dworkin [63]	Paterson et al. [12]
Distribution	Intragenerational Equity Intergenerational Equity Responsibility	Material Well-being Infrastructure
Procedure	Due Process Good Governance	Awareness Governance
Recognition	Availability[1] Affordability[1] Sustainability[1]	Relational Well-being

[1] van Uffelen [66] argues for this categorization.

Although Sovacool & Dworkin do not explicitly discuss recognition justice, it is a unique aspect of justice that can still be useful for contextualizing their recommendations. For example, due to the psychological pressures introduced by a lack of access to energy, either due to infrastructure or cost, interrupts relational well-being and is an injustice [66]. Further, (un)sustainable policies may be considered a misrecognition of the humanity of future generations.

Next, I examine the specific ways the social science literature understands how energy systems and their infrastructure (artifacts) contribute to the distribution of burdens.

2.2.3 Boundaries of Energy Systems

Previous work defined energy systems in purely technical terms as spatially, temporally, and topologically complex machines that coordinate the supply and demand of energy, especially electricity [43]. However, this definition neglects the ways energy systems may be used to construct and maintain power relations that contribute to inequitable distributions of burdens. Energy access is necessary to support complex modern economies and therefore possesses political power [67], [68]. The literature on the political economy of energy infrastructure locates this political influence in five distinct ways [68]. First, energy infrastructure affects competition and collaboration among nation-states in the geo-political sphere. The current situation in Ukraine makes this especially salient [69].

The second subset of the literature focuses on the process of energy infrastructure development and how these processes create social inequities. For example, energy policies that subsidize residential solar panels have not led to more equitable adoption of solar energy, with greater adoption in areas with higher income, among other social indicators [70]. Other popular arguments in favor of renewable energy assert that these energy sources are necessarily more egalitarian because the Sun and the wind cannot be (or have not yet been) privatized. Another is the urgency of climate change. While true, ignores or minimizes the potential environmental and social consequences of energy planning that does not consider energy justice [67]. Large-scale energy projects in the Global South have already led to the dispossession of nearby indigenous communities and other key actors [71], [72].

Third, the development of energy infrastructure is not simply conducted via policy measures, but also in the manner governments activate the public imagination in favor of these policies [68], [73]. Jasanoff and Kim (2009) articulate this concept as 'socio-technical imaginaries,' which are simultaneously descriptive and prescriptive of possible energy futures established by governments in the national zeitgeist [73]. This concept is demonstrated by the discourse surrounding nuclear energy in the United States and South Korea [73] as well as in Japan [74]. Governments can employ 'grand narratives' related to national security, climate change, or modernization to enhance public support while minimizing genuine participation [68].

Fourth, the political power of energy infrastructure can be traced further to the cultural values and policy choices embedded in the design and operation of seemingly technical systems [68]. In other words, the design and implementation of energy infrastructure may be used as a vehicle for apparently unrelated agendas, a form of "policy-making by other means" [68], [75]. Edwards and Hecht (2010) refer to the co-constitution of technological and political order as '*technopolitics*,' demonstrating the tangible material and political outcomes of technological systems [76].

Finally, energy systems and their infrastructure possess a unifying quality through which new political identities may evolve [68].

From these various perspectives, we can observe that confining an energy system to its technical characteristics is woefully incomplete. I propose that an energy system is a spatially, temporally, and topologically complex machine that coordinates the supply and demand of energy and acts as an important mediator of burdens that influence climate change risk. This thesis takes the important step of analyzing energy system planning and policy with this expanded definition.

The next section reviews current attempts to model energy systems and identifies gaps in conventional methods.

2.3 Modeling Energy Systems

ESOMs have several possible purposes such as forecasting future quantities, generating insight for policy development, or energy system planning for scheduling and acquisition [77], [78]. Table 2.2 summarizes the capabilities for a comprehensive list of energy system analysis tools. These tools are approximately sorted by mathematical formulation, e.g. explicit optimization or simulation. The "mixed-integer linear programming (MILP)" column indicates whether the framework uses a linear-programming approach to optimize an objective function. The "objective" column specifies the nature of the objective function if one exists. "Cost" objectives minimize total or annual energy costs, while "welfare" maximizes social welfare. Some entries have more than one objective listed. This means users may choose which objective to optimize. None of the tools in Table 2.2 are designed to handle simultaneous optimization (i.e. multi-objective optimization (MOO)). For those modeling frameworks that have an "objective" in Table 2.2, virtually all of them optimize system costs. EnergyScope is the only exception to this, which allows users to optimize GHG emissions. [79]. The "uncertainty" column indicates a feature to algorithmically generate model runs for testing either parametric or structural uncertainties. For example, EnergyScope is *suitable* for uncertainty analysis (i.e. many runs are computationally tractable) but does not have any built- in capabilities [79]. Some tools, such as NEMS [80], incorporate uncertainty into their calculations via learning curves. However, these learning curves require assumptions about learning factors and technological "optimism" – which are themselves uncertain [80]. Table 2.2 also indicates whether the tool is a "public code." This simply means users can download and inspect the source code. Other considerations for openness, such as licensing and development, vary among the listed frameworks. The other columns simply indicate the existence of particular features rather than the relative maturity or sophistication of each feature.

Frameworks, such as MEDEAS [81], and MultiMod [82], are general equilibrium models which embed energy systems within the macro-economy and facilitate the modeling of strategic behavior. The latter formulates a non-linear problem with the Karush-Kuhn-Tucker optimality condition [82], as opposed to more traditional linear programming methods. Models of this type are helpful for analyzing the economy-wide influence of policies but lack sufficient operational detail to be prescriptive for energy system planning.

Agent-based models are useful for modeling the market behaviors of different actors, such as firms (which produce power), transmission operators, and consumers. The latter category is typically aggregated for tractability. Modeled behaviors include technology preferences [83], [84], risk aversion [83], financial characteristics [83], [85], and information asymmetry among agents [83], [85]. Due to agent heterogeneity, agent-based models are considered useful for capturing social phenomena [78], [86].

A further set of tools focus on simulating power flow and demand fluctuations. CAPOW [87] generates synthetic data with statistical methods to explore uncertainties in energy dispatch and extreme demand events, but does not include any investment optimization based on these uncertainties. CESAR-P, SAM, Demod, and DESSTinEE focus on modeling demand profiles [88]–[90]. CESAR-P models individual building demand for energy based on the physical parameters of the building. However, it has no dispatch or investment optimization capabilities. Other tools such as Pandapower, GridCal, and SciGRID power model the infrastructure aspects of electricity systems – transmission and distribution – rather than the optimal dispatch of electricity producers [91]–[93].

Table 2.2: Summary of ESOM frameworks.

Model	Citation	math model type	MILP	Objective	Transmission	Sector			Investment Optimization	Physical Models	Forecasting	Agent Based	Uncertainty Analysis	Public Code
						Heat	Electric	Transport						
AnyMOD	[94]	Optimization	✓	Cost		✓	✓		✓					✓
Backbone	[95]	Optimization	✓	Cost	✓	✓	✓	✓	✓		✓		SP	✓
Balmorel	[96]	Optimization	✓	Cost	✓		✓		✓					✓
Calliope	[97]	Optimization	✓	Cost		✓	✓	✓	✓					✓
CapacityExpansion	[98]	Optimization	✓	Cost	✓		✓		✓					✓
DIETER	[99]	Optimization	✓	Cost		✓	✓		✓					✓
Dispa-SET	[100]	Optimization	✓	Cost	✓		✓		✓					✓
ELMOD	[101]	Optimization	✓	Welfare	✓		✓		✓					✓
ELTRAMOD	[102]	Optimization	✓	Cost			✓		✓					
EMMA	[103]	Optimization	✓	Cost			✓		✓					✓
EOLES elec	[104]	Optimization	✓	Cost			✓		✓					✓
ESME	[105]	Optimization	✓	Cost		✓	✓	✓	✓				MC	
ESO-X	[106]	Optimization	✓	Cost			✓		✓					✓
EnergyRt	[107]	Optimization	✓	Cost			✓		✓					✓
EnergyScope	[79]	Optimization	✓	Cost, GHG		✓	✓	✓	✓					✓
Ficus	[108]	Optimization	✓	Cost			✓		✓					✓
FlexiGIS	[109]	Optimization	✓	Cost		✓	✓	✓						✓
GAMAMOD-DE	[110]	Optimization	✓	Cost			✓		✓					
GenX	[111]	Optimization	✓	Cost	✓		✓		✓				MGA	✓
GRIMSEL-FLEX	[10]	Optimization	✓	Cost		✓	✓		✓	✓				✓
HighRES	[112]	Optimization	✓	Cost		✓	✓		✓					
MARKAL	[113]	Optimization	✓	Cost		✓	✓	✓	✓				MC, SP	✓
METIS	[114]	Optimization	✓	Cost	✓	✓	✓		✓				MC	✓
Medea	[115]	Optimization	✓	Cost			✓		✓					✓
Oemof	[116]	Optimization	✓	Cost		✓	✓	✓	✓					✓
OPERA	[117]	Optimization	✓	Cost	✓	✓	✓		✓					✓
OSeMOSYS	[118]	Optimization	✓	Cost		✓	✓	✓	✓					✓
OnSSET	[119]	Optimization	✓	Cost	✓		✓		✓					✓
PLEXOS	[120]	Optimization	✓	Cost			✓		✓				MC	
POLES	[121]	Optimization	✓	Cost			✓		✓					
POMATO	[122]	Optimization	✓	Cost	✓	✓	✓							✓
PRIMES	[123]	Optimization	✓	Cost	✓	✓	✓	✓	✓					
PyPSA	[124]	Optimization	✓	Cost	✓	✓	✓	✓	✓	✓			MGA	✓
REMix	[125]	Optimization	✓	Cost	✓	✓	✓	✓	✓					✓
REopt	[126]	Optimization	✓	Cost		✓	✓		✓					✓
StELMOD	[127]	Optimization	✓	Cost	✓		✓		✓					✓
Switch	[128]	Optimization	✓	Cost	✓	✓	✓	✓	✓					✓
TIMES	[129]	Optimization	✓	Cost, Welfare		✓	✓		✓				SP	✓
Temoa	[130]	Optimization	✓	Cost		✓	✓	✓	✓				MGA, MC, SP	✓
TransiEnt	[131]	Simulation	✓	Cost	✓	✓	✓							✓
URBS	[132]	Optimization	✓	Cost	✓	✓	✓	✓	✓					✓
Genesys	[30]	Optimization and Simulation		Cost			✓		✓					
OpenTUMFlex	[84]	Optimization and Simulation	✓	Cost		✓	✓	✓			✓			✓
PowNet	[133]	Optimization and Simulation	✓	Cost	✓		✓			✓				✓
Renpass	[134]	Optimization and Simulation		Cost			✓							✓
SimSEE	[135]	Optimization and Simulation		Cost			✓			✓				✓
MEDEAS	[81]	Other				✓	✓	✓		✓			MC	✓
MultiMod	[82]	Other		Welfare	✓	✓	✓	✓	✓					
NEMS	[80]	Other	✓	Cost	✓	✓	✓	✓	✓		✓			
Breakthrough Energy Model	[136]	Simulation			✓		✓		✓					✓
CAPOW	[87]	Simulation	✓	Cost	✓		✓				✓		✓	✓
CESAR-P	[88]	Simulation					✓			✓	✓			✓
DESSTinEE	[89]	Simulation	✓	Cost	✓	✓	✓			✓				✓
Demod	[90]	Simulation				✓	✓			✓	✓		MC	✓
EMLab-Generation	[137]	Simulation		Cost			✓		✓				MC	✓
EnergyPLAN	[138]	Simulation		Cost	✓	✓	✓	✓	✓					
Energy Transition Model	[139]	Simulation					✓							✓
GridCal	[92]	Simulation			✓					✓				✓
LoadProfileGenerator	[140]	Simulation				✓	✓			✓	✓	✓		✓
Pandapower	[91]	Simulation			✓					✓				✓
Pvlib	[141]	Simulation				✓				✓	✓			✓
PyLESA	[142]	Simulation		Cost	✓		✓	✓		✓				✓
SAM	[143]	Simulation								✓	✓		PA	✓
SciGRID power	[93]	Simulation			✓		✓							✓
SimSES	[144]	Simulation					✓			✓				✓
AMIRIS	[85]	Simulation and Agent-based					✓		✓			✓		✓
ASAM	[145]	Simulation and Agent-based			✓		✓					✓		✓
EMIS-AS	[83]	Simulation and Agent-based	✓	Welfare	✓		✓					✓	✓	✓
Lemlab	[146]	Simulation and Agent-based	✓	Welfare			✓					✓		✓
MOCES	[147]	Simulation and Agent-based		Cost			✓			✓		✓		

2.3.1 Economic Dispatch and Social Welfare

Linear programming (LP) or MILP are the dominant optimization approaches among the frameworks in Table 2.2. Economic dispatch models optimize the power output of *dispatchable* generators in a model system [41], [148]. They all share the same fundamental formulation.

Minimize

$$F(x) = \sum_i C_i x_i \tag{2.1}$$

subject to,

$$g(x, p) \leq 0.$$
$$x \in \vec{X}$$

where

$\vec{X}$ is the set of decision variables,

C_i is the *i-th* cost,

g is some linear inequality constraint.

The exact formulation of Equation 2.1 may vary slightly across models, but the objective for most economic dispatch models is to minimize total cost. The near universality of a cost-based objective function comes from the concept of *social welfare maximization*. This concept is illustrated in Figure 2.4.

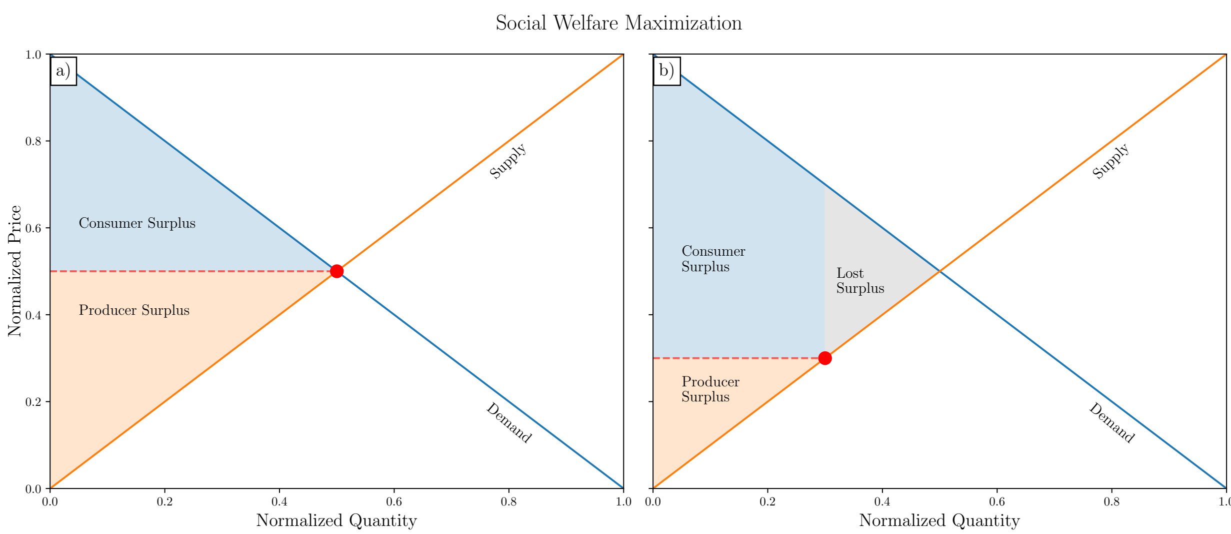

Figure 2.4: Demonstration of "social welfare maximization." Plot a) shows the total surplus when the price is at equilibrium. Plot b) shows the total surplus when the price is artificially depressed.

In microeconomics, social welfare is identical to the sum of consumer and producer surplus. Therefore social welfare is maximized when the sum of these two quantities is maximized. Figure 2.4 shows this case on the left panel. However, if an economic policy capped the price of some product at a price lower than the equilibrium price then the consumer surplus expands, and the producer surplus contracts, as shown in the right panel of Figure 2.4. Nobody receives the "lost surplus" because suppliers do not produce more despite unmet demand for the product because the price is capped. Typically, modeling tools consolidate the demand curve to a single value. In this case, social welfare maximization is approximated by minimizing the total cost of energy [137]. This simplification is valid because demand for energy is highly inelastic [106], [149]–[151]. Figure 2.5 shows the impact of highly inelastic demand.

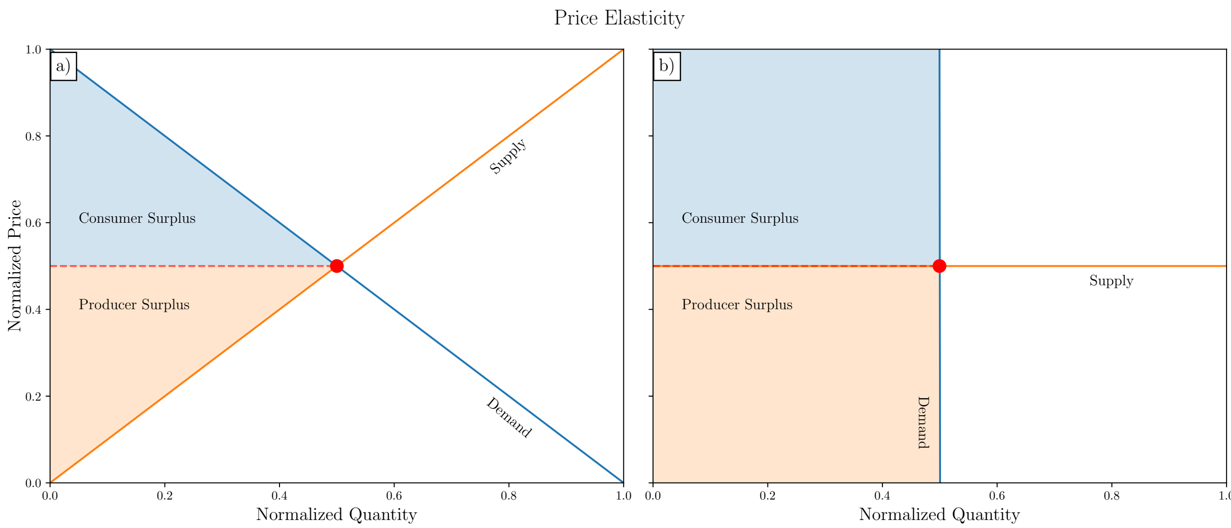

Figure 2.5: Demonstration of "price elasticity." Plot a) shows a typical supply-demand curve where changes in price lead to proportional changes in demand. Plot b) shows an inelastic demand where consumption does not change proportionally with price.

For an elastic good supply and demand are in proportion with each other. An increase in the supply leads to a proportional increase in demand via a reduced price, eventually returning to an equilibrium price (shown in Figure 2.5a). However, as Figure 2.5b demonstrates, an inelastic demand does not respond proportionally to changes in price, such that consumers become "price- takers," paying the price set by producers. Importantly, in the latter case consumer surplus is infinite and minimizing the energy cost through policy mechanisms does not create a lost surplus as shown in Figure 2.4b. Since electricity demand is highly inelastic, economic dispatch models minimize the cost of generating electricity. Although optimizing welfare, rather than the total cost, is useful for disaggregating multiple demands for the same commodity [101], this thesis adopts the former, simplified, approach to economic dispatch.

2.3.2 Accounting for Uncertainty

Due to the complexity of our energy system, handling uncertainty is one of the most important features for ESOMs [77], [78]. There are broadly two types of uncertainties: parametric and structural. The former method refers to uncertainty around the value of some empirical quantity (e.g. price of fuel or the discount rate). In many cases, these quantities are better represented by *distributions* which may be sampled using formal methods like Monte Carlo (MC) or parametric analysis (PA) [78], [152]. Deterministic codes such as TEMOA, TIMES, or ESME use these techniques to generate many model runs. Another method for handling parametric uncertainty is stochastic programming (SP), where parameters are replaced with non-linear risk functions [78], [153]. Although parametric uncertainty is important the analysis of uncertain values is not a focus of this thesis.

Structural uncertainty relates to *unmodeled objectives* [77], [78], [154]. There are few formal methods to address structural uncertainty due to its qualitative nature. The most common approach to handling this type of uncertainty is using Modeling-to-Generate-Alternatives (MGA) to probe the near-optimal decision space [41], [77], [111], [152], [155]. DeCarolis wrote, "[p]olicy-makers often have strong concerns outside the scope of most models (e.g., political feasibility, permitting and regulation, and timing of action), which implies that feasible, sub-optimal solutions may be preferable for reasons that are difficult to quantify in energy economy optimization models" [77]. Therefore, an "optimal solution" may lie in the model's inferior space [77]. Section **??** details the implementation of MGA. This perspective centers policy-makers as the beneficiaries of modeling efforts. It also forces a high-level perspective where economics becomes the overriding concern, when local municipalities may have a unique set of interests, which may or may not include economics.

Another strategy to handle structural uncertainty is optimizing multiple objectives simultaneously. However, some researchers dismissed this approach for the following reasons [77]:

1. structural uncertainty will always exist, regardless of the number of modeled objectives;
2. traditional MOO enables the exploration of the Pareto-front, but not the near-optimal space;
3. analyzing tradeoffs for problems with many objectives is tedious.

These critiques may explain the distinct lack of frameworks that apply MOO for energy system problems. However, there are important benefits to MOO, and the lack of an energy system *framework* to apply this technique is one of the gaps this thesis fulfills.

2.4 Multi-objective optimization in Energy Systems

A multi-objective problem may be formulated as

$$\min \quad \{F_1(x), F_2(x), ..., F_i(x)\}, \tag{2.2}$$

subject to

$$g(x,p) \leq 0.$$
$$x \in \vec{X}$$

Where Equation 2.1 had a single objective $F(x)$ to minimize, Equation 2.2 has a *set* of objectives, $\{F_i(x)\}$. Rather than identifying a global minimum point, the solution to Equation 2.2 is a *set* of non-dominated points along a non-inferior region called a Pareto-front. Each point on this frontier cannot improve one objective without making another objective worse, hence "non-dominated." Generally, for competing objectives, there will be an infeasible space that is not attainable by the given combination of objectives. For a minimization problem, the space above the Pareto-front is the sub-optimal feasible space. This is the space that MGA promises to search for a corresponding single-objective problem. Figure 2.6 illustrates a set of solutions along a Pareto-front for an example problem from Multi-Objective Optimization in Python (`Pymoo`) [156], [157].

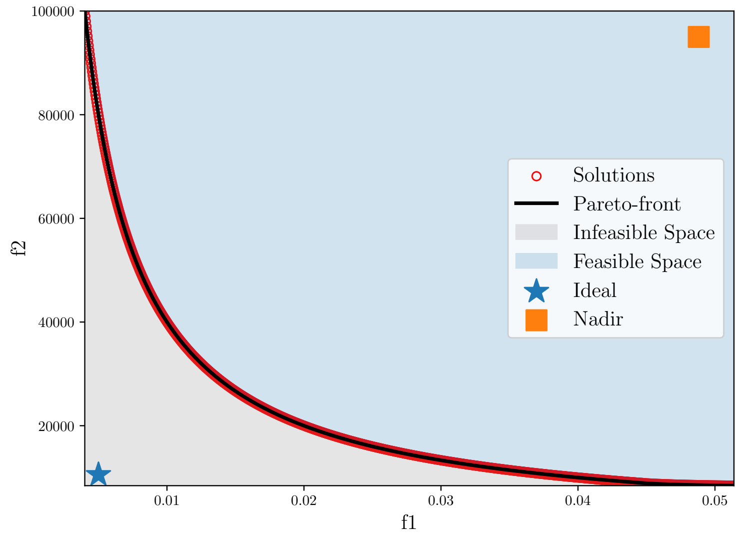

Figure 2.6: An example *convex* Pareto-front from `Pymoo` [156], [157].

There are broadly two classes of MOO algorithms for solving Equation 2.2, *scalarization* and *population-based* [158], [159]. Scalarization approaches map the multi-objective problem onto a set of single-objective problems using variation of parameters. In the weighted-sum (WS) algorithm, the objectives are assigned weights, w_i, and the aggregated objective becomes

$$\min \quad J(x) = \sum_i w_i F_i(x) \tag{2.3}$$

subject to the same constraints as Equation 2.1 [158], [159]. These weights are varied in order to sample points along the Pareto-front. Alternatively, the ϵ-constraint (EC) algorithm chooses one objective from $\{F_n\}$ to solve and converts the others into constraints, whose bounds are denoted by ϵ. These bounds are varied until the desired number of points on the Pareto-front is reached [158], [159]. This problem can be written as

$$\min \quad F_1(x), \tag{2.4}$$

subject to,

$$\begin{aligned}
&F_2(x) - \epsilon_1 \leq 0 \\
&\vdots \\
&F_i(x) - \epsilon_1 \leq 0 \\
&g(x, p) \leq 0, \\
&x \in \vec{X}.
\end{aligned}$$

The sub-problem, Equation 2.4, must be repeated for each ϵ_i.

Scalarization is attractive due to its simplicity. However, this approach is sensitive to problem convexity. WS will never be able to sample points in a concave region of the Pareto-front, and EC will have poorly spaced samples along a concave region. Further, these algorithms can only sample points on the frontier, not the sub-optimal feasible space. Thus supporting the critique of using MOO for handling structural uncertainty [77]. Fortunately, population-based algorithms, also called *genetic algorithm (GA)* or *evolutionary algorithms*, resolve some of these issues by solving Equation 2.2 directly. GAs are based on the principle of natural selection. In a GA, such as Non-Dominated Sorting Genetic Algorithm-II (NSGA-II), an initial population is randomly generated using the problem's decision variables, the 'fitness' of this population (i.e. performance on each objective) is calculated, then a new population is selected from the 'fittest' (most optimal) individuals. This process continues until a convergence criterion is reached. The advantages of this method are

1. a guaranteed solution, regardless of convexity,
2. no prior knowledge is required to initialize the problem, as with EC,
3. greater diversity of solutions (i.e. spacing of points along the Pareto-front),
4. the sub-optimal space is sampled through the iterative process (though not uniformly).

Specifically, point four address one of the primary criticisms of using MOO to reduce structural uncertainty by obtaining points in the inferior region [160]–[162]. An additional advantage of GAs is the ability to incorporate more physics and simulations into the optimization procedure than LP, MILP, or scalarization allow [160].

Previous work handled structural uncertainty using MGA which samples unique solutions from the sub-optimal space in a neighborhood around the global minimum for a single objective [77]. Researchers argue that this approach is valid because there will always be structural uncertainty and sampling the inferior region may offer insight for decision-makers. While structural uncertainty may persist it is not *irreducible*. By increasing the number of modeled objectives MOO reduces structural uncertainty. Further, ideas from MGA can be applied to MOO by efficiently sampling the near-optimal space [160]–[163]. The goal of MGA is to find a *reduced* set of maximally different alternatives to provide insight, where analyzing the full set of alternatives would be overwhelming [77], [163]. Figure 2.7 shows the near-optimal space around the Pareto-front from Figure 2.6.

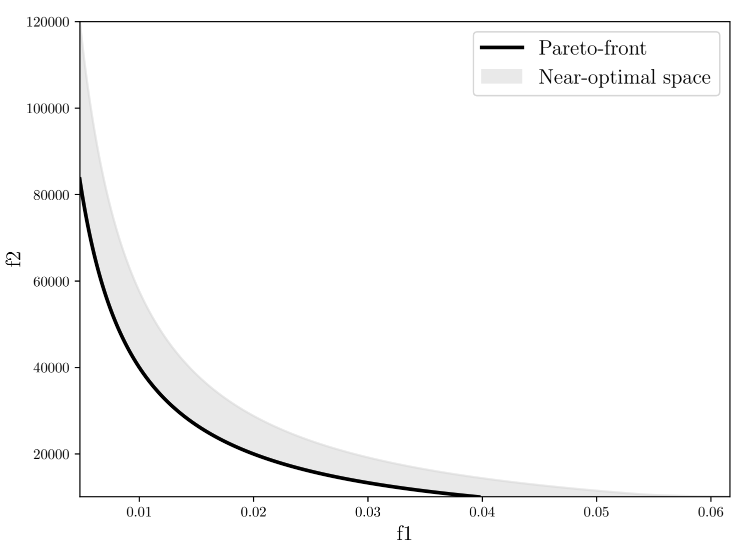

Figure 2.7: The near-optimal space around the Pareto-front.

For these reasons, this thesis explores energy systems optimization and the handling of structural uncertainty through MOO and GAs. Section **??** reviews the details of the GA used in this thesis.

2.4.1 State-of-the-art (RENAME?)

It is well understood that engineering and policy problems, which include energy systems optimization, often require satisfying multiple antagonistic objectives [160]–[162], [164]. However, the application of MOO to energy systems in the literature is limited. Table 2.3 summarizes the current body of work. As before, the "public code" column only indicates if the source code is accessible. Additionally, the "sector" columns only indicate the presence of a feature, not the relative maturity or sophistication of the modeling. There are six "objective columns," indicating which objectives are considered the in the model or study. A "technology" objective might optimize a specific technology or set of technologies. For example, maximizing the percentage of renewable energy in a system. The "reliability" metric varies among studies, but generally refers to the potential for load loss. For all of the studies in Table 2.3, the "environmental" objective refers to GHG or "global warming potential" [165]. Although it could refer to other environmental impacts such as land use, water use, or thermal pollution.

Table 2.3: MOO used with energy systems.

Citation	Model	Algorithm	Objectives						Sector			
			Economic	Social	Environment	Reliability	Technology	User-defined	Heat	Electricity	Transport	Public Code
[166]		NSGA-II	✓			✓	✓			✓		
[167]		NSGA-II	✓				✓			✓		
[168]		NSGA-II	✓		✓				✓	✓		
[169]	Oemof-moea	NSGA-II	✓		✓				✓	✓	✓	✓
[170]	HYRES	GAToolbox	✓			✓				✓		
[171]		NSGA-II	✓		✓				✓	✓		
[172]		WS	✓		✓				✓	✓	✓	
[62]		NSGA-II	✓		✓				✓	✓		
[173]		NSGA-II	✓		✓				✓	✓		
[174]	SIREN	WS	✓		✓	✓				✓		✓
[165]		EC	✓		✓	✓			✓	✓		
[175]		NSGA-II	✓			✓				✓		
[176]		NSGA-II	✓			✓				✓		
[177]		NSGA-II	✓		✓				✓	✓		
[178]		EC	✓		✓	✓			✓		✓	
[179]		NSGA-II	✓		✓					✓		

Most of the studies in Table 2.3 used NSGA-II to identify the Pareto-front with a few using scalarization. Consistent with the trend shown in Table 2.2, every study in Table 2.3 uses some economic or "cost" metric as one of the objectives. Also consistent, is that none of these studies identified a metric to optimize over social concerns. Laha et al. [167] used fatalities per GWh and employment per GWh as criteria for social sustainability, but these were not objectives in their model, rather they were calculated *ex post facto* with scenario analysis. Riou et al. [166] investigated the tradeoffs among renewable share, reliability, and total cost. Their findings were consistent with single objective scenario analysis [47], that greater renewable penetration leads to greater costs and less reliable energy with a 100% renewable energy system being the least reliable or incurring the greatest costs [166].

Although previous work demonstrated the applicability of MOO to energy systems optimization, there are significant limitations.

- There are at most three modeled objectives [165], [166], [178].
- Where traditional ESOMs have many mature frameworks (as shown in Table 2.2, there are no frameworks that use MOO. Simultaneously, none of the studies in Table 2.3 developed a framework. Prina et al.

developed a bespoke and unlicensed model called "Oemof-moea," however this does not constitute a framework.

- None of the studies in Table 2.3 allow user-defined objectives, because none of them have *users*.
- None of the studies incorporate social metrics into the modeled objectives.

This thesis develops, Open source multi-objective energy system framework (`Osier`), a novel energy systems framework using MOO that fills these gaps by using GAs that allows for efficient modeling of many objectives, enabling user-defined objectives, providing the option to make metrics of interest either objectives or constraints, and incorporating ideas from MGA to provide insight from the sub-optimal objective space.

If carbon emissions should not be considered an objective, but rather a constraint, because there are hard emissions budgets why can't the same argument be made with respect to cost? Some places might have limited funds to allocate for energy infrastructure.

Chapter 3

Conclusions

We conclude that graduate students like coffee.

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