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PNNL-33571

Building a better framework for evaluating human well-being impacts in global change analysis

The example of energy security

September 2022

Siwa M Msangi
Stephanie T Waldhoff
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Abstract

Human well-being can be greatly impacted by the global environmental and socio-economic change captured in Integrated Models of Global Change (IMGCs). Though most IMGCs address some aspects of well-being, their underlying modeling approach and 'philosophy' differ widely, and some key elements – like energy security – are omitted. In this report, we describe a project in which we set out to a create a framework through which the well-being dimensions of the household are connected to key drivers of socio-economic and environmental change – and how the needed metrics, data and modeling methods can be brought to bear. We focus on the well-being dimensions of energy, and lay out the necessary elements to capturing household energy security – using household energy burden as the relevant metric. We begin by showing the conceptual linkage of energy burden to environmental drivers like temperature change, using a simple and straightforward conceptual framework. We then go further to use the example of GCAM-USA to show how some key analytical features of the model can provide insight into how energy security across different groups can change along alternative pathways to sustainability. We compare our preliminary assessment of household energy burden to existing data and suggest further steps to improve and refine this analysis in future research.

Summary

The authors undertook a Laboratory Directed Research & Development(LDRD) funded research initiative, in the summer of 2021, to better understand the key elements for defining human well-being within the context of socio-economic and environmental change. The initial discussions among the research team led to a better understanding of how well-being dimensions, across the domains of energy, water and food relate to drivers of change, and how the relevant metrics (and the needed data for quantifying them) could be combined with existing and yet-to-be-built modeling frameworks. This initial summer activity, became part of a bigger LDRD-funded 'Agile Investment' initiative by PNNL – the *GODEEEP* project, which incorporated the key elements of this original research work as one of the key tasks, under a key research objective aimed at understanding the equity and well-being implications of deep decarbonization efforts in the US.

In order to focus this work more concretely on some key research priorities and interests of the lab (and the *GODEEEP* project) – we focused our attention on the energy domain, in order to better understand how key metrics of household energy security could be quantified and modeled, within the forward-looking projections of the GCAM-USA model. Building from an initial conceptual framework linking drivers of change to well-being – and making use of the previous work to disaggregate the residential energy demand within the GCAM-USA model across 5 socio-economic groups (Sampedro *et al*, 2021) – we illustrated our approach with projections of household energy burden across the income quintiles for each state in the US. While our projections show a higher energy burden than what is observed in US Bureau of Labor Statistics data – they provide a useful starting point for understanding the necessary methodological and data improvements that need to be made in order to move this work forward.

Key abbreviations used

BLS	Bureau of Labor Statistics
EBSD	Earth and Biological Sciences Directorate
EED	Energy and Environment Directorate
EIA	Energy Information Administration
GCAM	Global Change Analysis Model
LDRD	Lab Directed Research and Development
IMGC	Integrated Model of Global Change
GODEEEP	Grid Operations, Decarbonization, Environmental and Energy Equity Platform
RECS	Residential Energy and Consumption Survey

Acknowledgments

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1.0 Introduction

The effects of societal development, environmental change, and policies related to climate, land, energy, and socioeconomic systems will affect many aspects of human well-being (e.g. energy and food security), with differential impacts across regions and socio-economic groups. The metrics for environmental outcomes – such as CO_2 concentrations, soil carbon levels or nitrogen/phosphorus loadings – have been better-developed within integrated human-earth system modeling frameworks, compared to those for human outcomes (such as energy security, food security or health effects).

In this report, we focus on the question of energy security and synthesize the various approaches to capturing consumer-level energy use and adequacy (relative to needs) within Integrated Models of Global Change (IMGCs) and point to important points of scientific advancement, methodological challenge and ongoing contention in the literature. This was the overall goal of the PNNL-provided Lab Directed Research Development (LDRD) funds that were allocated to the topic of addressing human well-being issues in integrated modeling of global change. We use the example of GCAM-USA, as an illustration of how residential-level energy security could be modeled within an IMGC – and measured across different socio-economic groups. We show where better data and further research and collaboration with sector experts could be beneficial to addressing key science questions, informing energy strategy, and providing insight into possible pathways to achieve future low-carbon energy transitions, while keeping equity and key sustainable development goals in mind.

Before further describing the analytical framework for capturing human well-being dimensions within IMGCs, such as GCAM-USA, we begin with a brief description of the LDRD-funded project, and how it has progressed and evolved to its current state – as a sub-task within a larger LDRD-funded 'Agile Investment' by PNNL to explore the technological needs and societal implications of deep decarbonization – the *GODEEEP* project.

1.1 Background to the initial LDRD-funded project on well-being

During the summer of 2021, PNNL awarded LDRD funding to JGCRI to begin researching key ways to improve the incorporation of human-well being impacts analysis into global change research. The project – titled 'Constructing a Framework for Evaluating Human Well-Being Impacts in Global Change Analysis' – set out to accomplish the following key objectives:

1. To build a usable and useful framework for understanding human well-being that could be directly linked to the global change-related research that PNNL does

2. To consider the key drivers of well-being change, and how they might interact with other key system-level drivers of global socio-economic and environmental change – so that we might better understand how to utilize the suite of analytical tools currently used within the EBS and EE Directorates of PNNL to model these linkages

3. To pay primary focus to the dimensions relating to energy security, as a first step, given the overall research strengths of the lab, and the immediate needs coming from ongoing project work that needed to be informed by this research

4. To utilize whatever insights we could obtain from the current literature, as well as from out own internal consultations and discussion across EBSB and EED staff – to propose a framework that could accomplish the analytical requirements of well-being impact analysis under global change.

The proposal of the LDRD-funded project identified some of the key elements of well-being that should be addressed in the research, and which are critical to building a useable analytical framework. The proposal promised to lay out what is needed for creating a useful and coherent framework for human well-being, in terms of:

- Defining the necessary metrics for identifying which well-being outcomes matter
- The necessary data for capturing these metrics, and which are needed to parameterize the models that will simulate the indicators of those metrics will evolve over time
- The necessary modeling elements that are needed to operationalize the quantitative assessment of how human well-being evolves and interacts with key drivers of change

We recognized, from the outset of the project, that the modeling components that we identified would have to be able to connect the metrics of interest to well-being analysis to the essential 'domains' we tend to work with in global change research – namely: population, planet (i.e. earth system) and profit (i.e. the economy). Besides making the connection to these 3 essential domains, the analytical modeling framework would also have to capture the dynamics of change and systems evolution that come about in response to key drivers of global socio-economic and environmental change.

1.2 Project activities and progress from FY21 to present

The project began in the summer of FY21 with a series of meetings between key researchers in the EBS and EE Directorates of PNNL – namely, Siwa Msangi (project PI), Stephanie Waldhoff, Jim Yoon and Daniel Brent – to scope out the dimensions of human well-being that could be addressed within the short time remaining in FY21, as well as beyond it.

An initial scoping of the literature was done in order to better understand how the human well-being dimensions of global change have been addressed, and the extent to which such analytical work has been carried out within IMGCs. Early on in the project, we decided to maintain a tight focus around energy security – given the emerging interest within PNNL to explore the socio-economic equity and well-being dimensions of deep decarbonization initiatives being proposed by the US administration of the day. Towards that end, we began to examine the metrics that could capture important well-being dimensions around household energy use

To push forward our research agenda – we put priority on identifying the data set that could be used to capture the indicators of energy burden and insecurity on a regional level, and to identify the parts of the GCAM-USA model that could be used to project these forward.

Below is a table which shows the projected milestones that were envisioned at the outset of the project, during the summer of FY21, and how the were intended to progress into FY22.

Table 1. Milestones and achievements of the project in FY21 and FY22

Intended milestone	Target Date	Notes on progress/completion
Summary of key ideas on metrics, data sources and modeling approaches	End of summer/FY21	Documented in this report
Completion of initial literature review	End of 1st quarter FY22 (Dec 2021)	Review of literature done, but not annotated
1st draft of conceptual framework of proposed metrics, data & modeling approach	End of 2nd quarter FY22 (Mar 2022)	Presented at the kickoff meeting of the *GODEEEP* project on 9th Feb 2022
Revised design document with more detailed description of metrics, data and methodology	End of 3rd quarter FY22 (Jun 2022)	Not completed – still forthcoming
Research manuscript containing use cases for well-being analysis in global change research	End of 4th quarter FY22 (Sept 2022)	forthcoming

Given the very short time that was left in FY21, from the outset of the project, we were only able to do a very cursory scoping of the food energy and water domains – in order to understand how the key well-being components relevant to each could be explored in potential 'use cases'. See Appendix B for a description of these use cases.

In the specific domain of energy, most of the significant progress in analytical thinking, clarification, data exploration and model design were carried out during FY22 – as part of the GODEEEP 'Agile Investment' project that incorporated the analysis of household energy security as one of the tasks under its second research objective. Please see Appendix A for a more complete description of the GODEEEP project, to give a better context as to how the thinking undertaken in this initial LDRD-funded research effort is currently being extended into the wider project.

2.0 Household Energy Security

In this section, we go into greater detail to describe how the human well-being dimensions relating to energy can be conceptualized and modelled within integrated modeling frameworks. We begin with an overview of how energy fits into the overall economy of the household, and how the well-being dimensions of energy overlap with those related to food and other household necessities. Following this, we go into more detail on how household energy security can be measured, and the how the relevant metrics can be observed in data and captured within an integrated model of global change (IMGC) such as GCAM-USA.

2.1 The role of energy in the overall well-being of the household

Addressing the issue of energy security at the consumer level involves issues that fall within the economics of the household, and the various factors that determine the balance between income, assets and expenditure. Like food security – the factors that determine a lack of energy security are often linked to a lack of access to energy sources (either due to their distribution/proximity or affordability), a lack of stability in the supply of energy – or the usability of the energy (as determined by the carrier and the technology available for its conversion into usable services). The table below shows how those different aspects of energy security line up analogously with those of food security – and the kinds of measures that can be used to assess each component of energy (in)security.

Table 2. Key aspects and relevant indicators of energy security – and its congruence with the conceptualization of household food security

Key aspects of energy security	Potential indicators	Equivalent food security concept
Adequate heating/cooling	Levels of thermal discomfort	Access
Affordability (energy burden)	% of household budget spent on energy services	
Reliability	Frequency of outage/supply failure	Stability
Usability	Does it come in a form I can use (of sufficient quality)?	Utilization

Just as the concepts of food security – as described by the well-known framework put forward by the Food and Agricultural Organization (FAO) of the United Nations (FAO, 2008) – can be applied to either an aggregate national or regional-level, or at household-level; the same can be said for energy security. Especially with regards to issues of affordability – which relates directly to the ability of the household to accommodate energy-related expenditures into its total household budget – the important dimensions of energy security relate to its internal economy. The ability to stabilize energy supply is typically out of the scope of households to directly control – although they can mitigate the effects of energy supply instability with the purchase of individual generators, or the use of alternative energy sources (solar, batteries) to try and smooth their supply. But the differential ability of households to afford such measures touches on the equity dimensions of energy access, and the limited ability of poorer households to cope with shortages and disruptions.

Thinking more broadly about the household-level economy, and how the household interacts with the wider economy to obtain income and provision the goods and services that it needs – we can see how the need (and affordability) of energy services fits in quite easily. Though some households can obtain energy directly from the environment – such as the ability to obtain firewood (through direct harvesting) – others have to rely upon markets and established provisioning networks (e.g. utilities) to obtain their energy supplies. How the expenditures for energy services, competes with other necessary purchases for goods and services highlights the 'heat or eat' tradeoff that has been noted in the literature (Hills, 2012; Snell *et al,* 2018).

The graphic below shows how household-level well-being is tied to various components of the household economy – and its relation to labor/wage markets, personal wealth as well as the markets for goods and services it consumes.

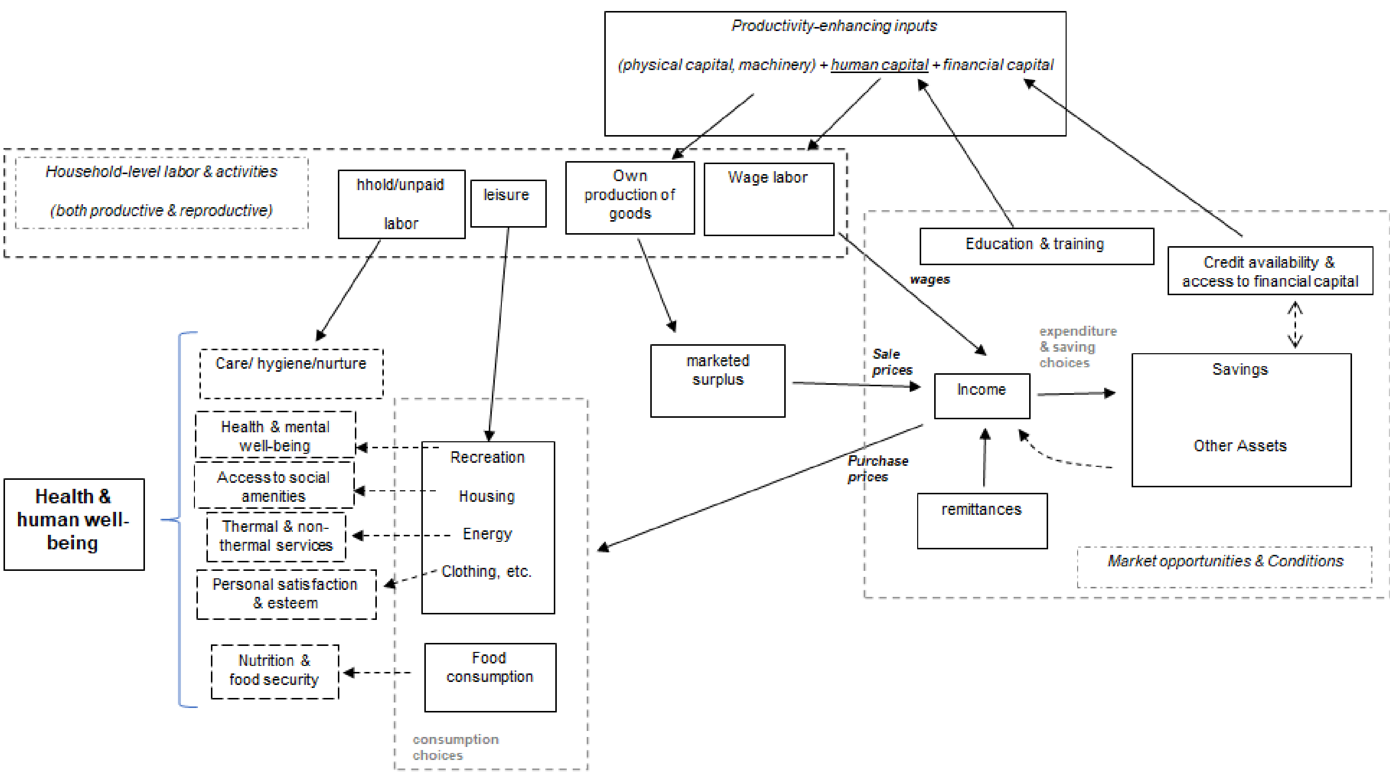

Figure 1. Key socio-economic linkages to household health and well-being outcomes

The fact that energy and food compete for the same (limited) budget is captured in this schematic, and the same price or availability shocks that would affect the ability of a household to obtain one kind of good, will have a simultaneous effect on its ability to obtain the other.

2.2 Conceptual model of key drivers relevant to energy security

In order to better conceptualize how the key indicators and drives of energy (in)security might be captured within a quantitative model, we think through the specific pathways that might link important drivers of socio-economic change that affect the demand side of an energy market to the price-related outcomes that impact human well-being (as shown in Figure 1, previously). We look more specifically at the pathways that affect the interaction of energy supply and demand in a model such as GCAM-USA, and link them to specific outcomes of energy security – as is shown in the figure below.

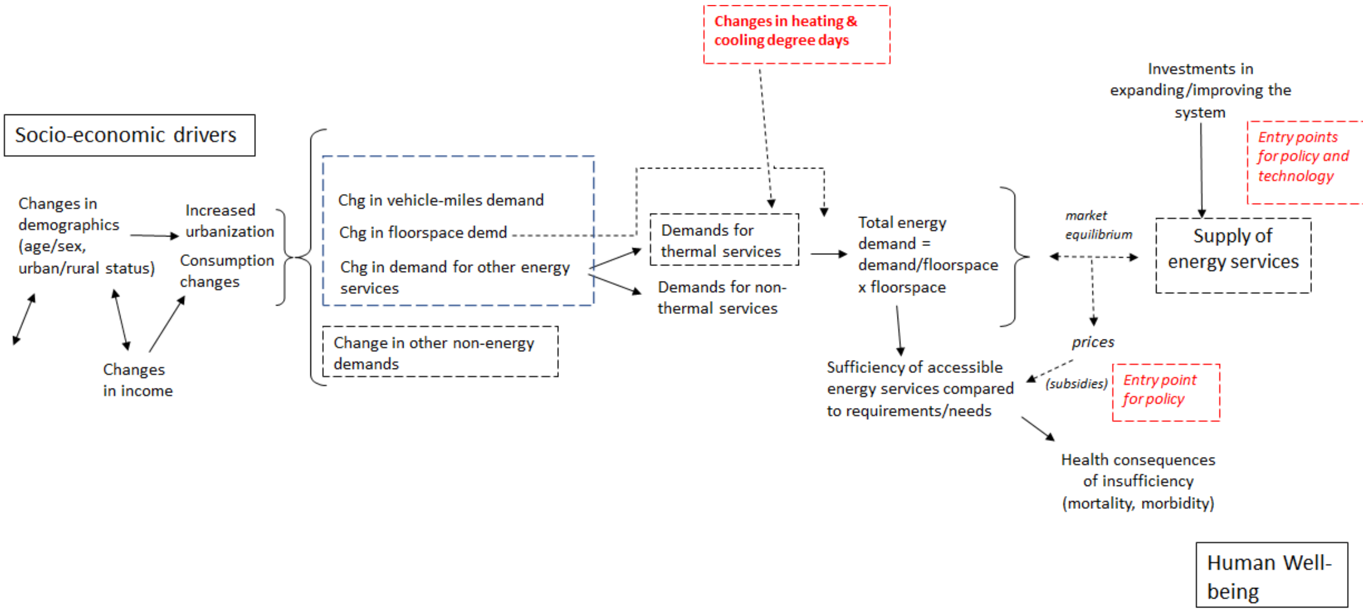

Figure 2. Key drivers of change and their influence on well-being and energy security

In this figure, we see that some drivers of change (such as population and income growth) have the effect of growing the scale of overall energy demand within an economy – by increasing the number of consumers and their per-capita energy consumption patterns (as they become better able to afford – and acquire tastes for – different kinds of energy services). We also see, from this figure, that energy demand can also be affected by environmental factors such as the number of hot or cold days – that require the use of thermal services for cooling or heating, respectively.

Even without having a quantitative model to illustrate how a change in heating and cooling-degree days might cause households to spend more on energy (and increase their energy expenditures as a share of overall household spending – i.e. their 'energy burden'), we can conceptualize how this relationship might play out with the use of a conceptual model.

In the figure below, we show the 4 quadrants of a schematic, in which the upward sloping relationship between heating and cooling-degree days and the demand for thermal energy services needed to maintain household levels of comfort.

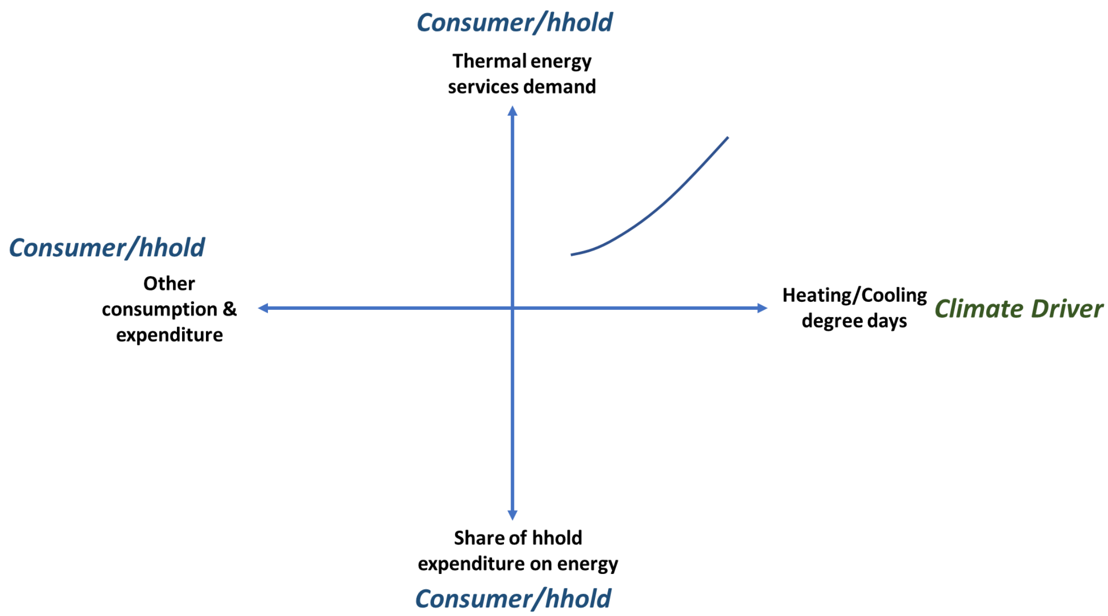

Figure 3. A four-quadrant conceptualization with upward-sloping demand for thermal energy services in response to increasing HDD/CDD

The argument for requiring additional HDD or CDD to be met with a further expenditure of energy to provide thermal services is intuitive, and doesn't require further explanation or elaboration. The figure below shows how the increasing expenditure on thermal energy services might crowd out the purchasing ability towards making other expenditures, under a limited household budget – defined by the simple equation: $Income = Cost_{ThermEnergy} \cdot Cons_{ThermEnergy} + Expenditure_{non-energy}$

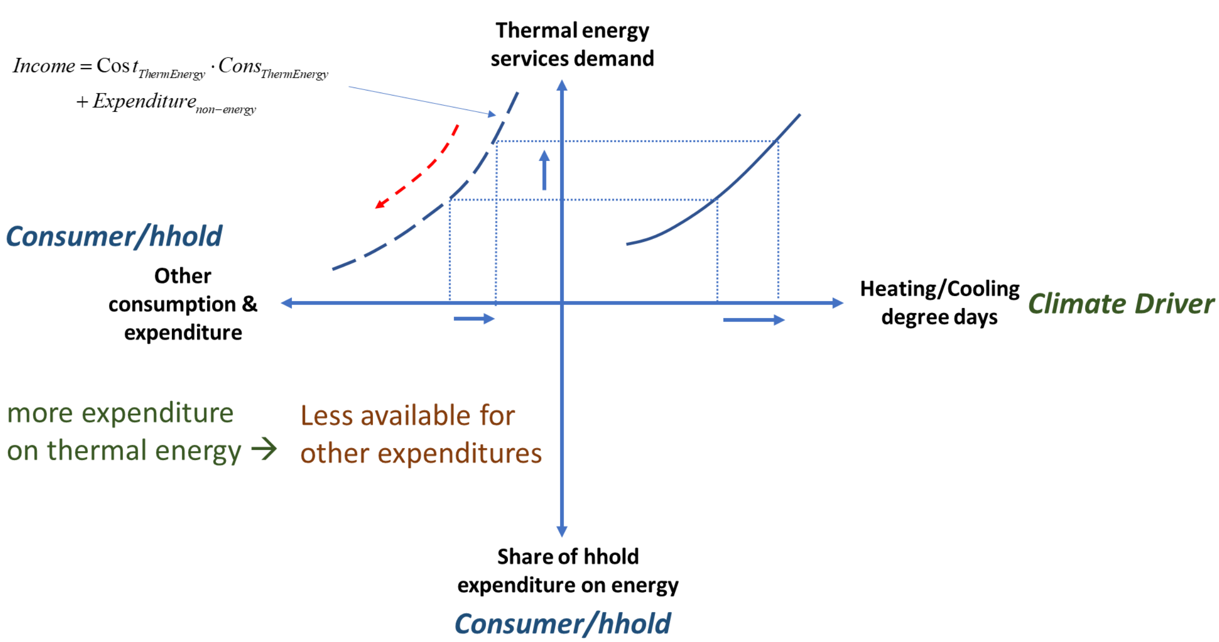

Figure 4. The crowding-out of other expenditures with increasing demand for thermal services in the 2nd quadrant of our conceptual model

Again, this one-to-one mapping between the expenditure on thermal energy services and the decreasing ability to make expenditures on other goods and services, under a fixed household budget, is intuitive and doesn't require further explanation or argumentation.

Naturally – as the magnitude of household expenditures on energy services rises, one would expect that the share of that expenditure on the household total would also rise – thereby increasing the energy burden of the household. This is captured in the 3rd (south-west) quadrant of the figure below.

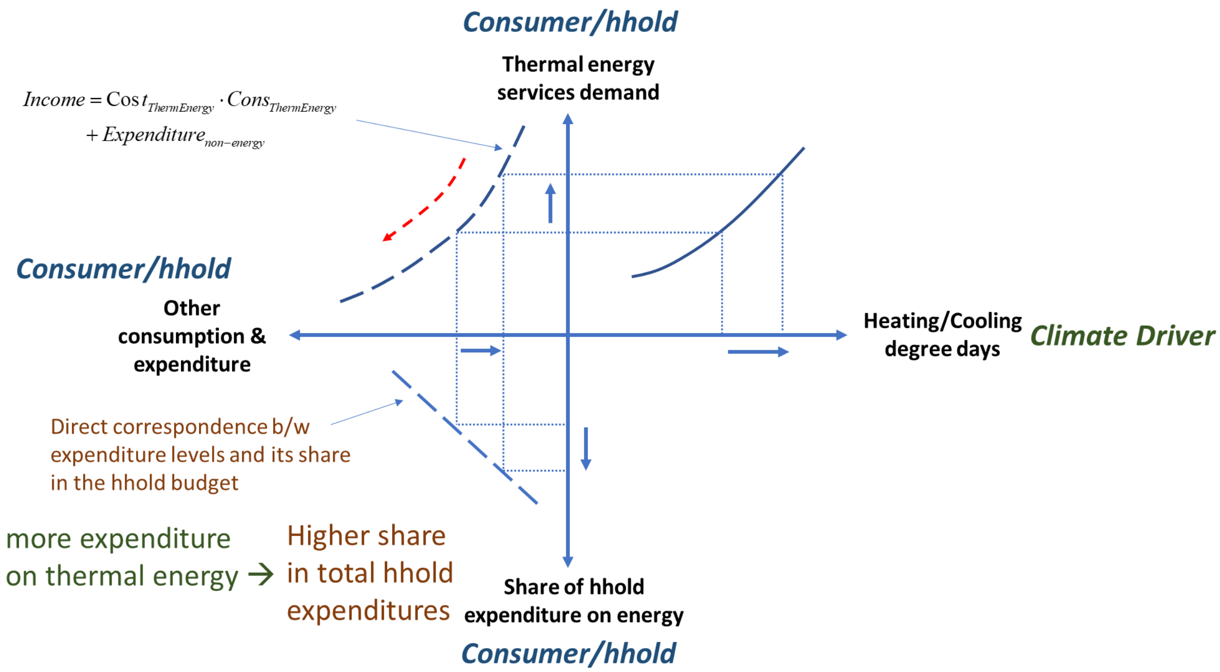

Figure 5. The increasing share of energy in household expenditure (i.e. "energy burden") in the 3rd quadrant of our conceptual model

Based on this – we can therefore trace out the direct relationship between an increase in heating- and cooling-degree days and the energy burden of a household, in the 4th quadrant of the schematic, as is shown below.

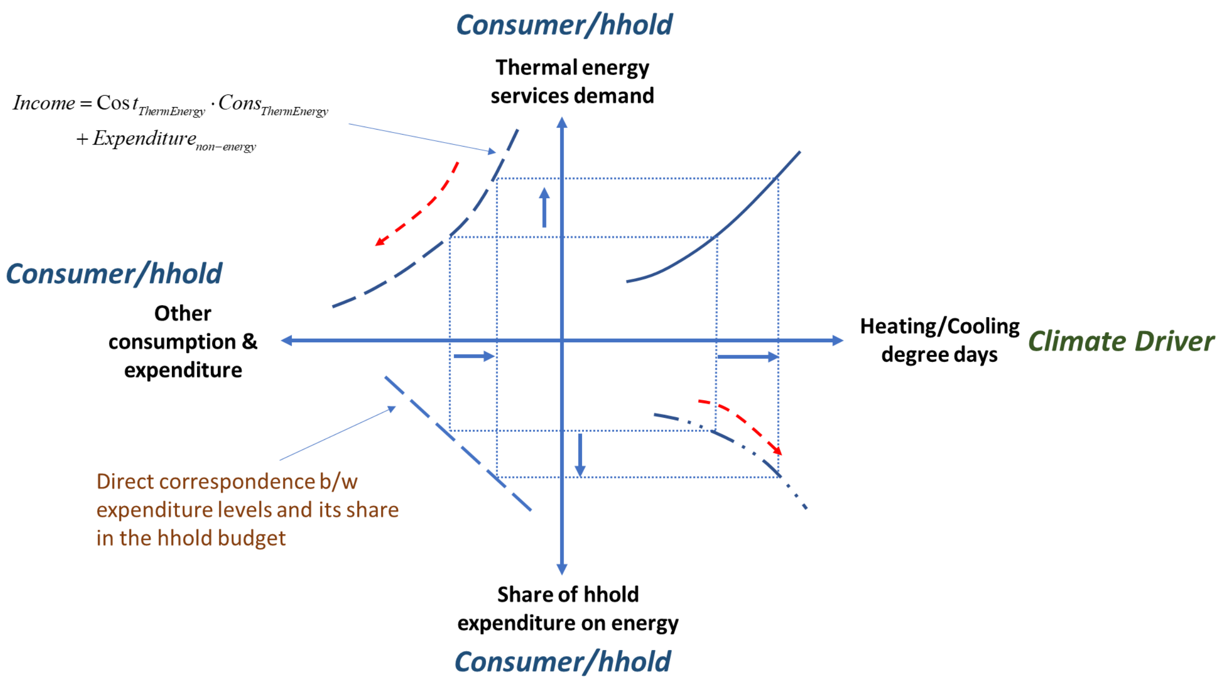

Figure 6. The correspondence between increasing HDD/CDD and household energy burden traced out in the 4th quadrant of our conceptual model

Moving from this conceptual representation of how key socio-economic and environmental drivers can affect a key indicator of household energy security, we now describe a quantitative analytical framework that can capture this (among other key linkages) within the context of global change.

3.0 Analyzing energy security in an integrated model

In this section, we go into more detail on how household energy security can be measured, and the how the relevant metrics can be observed in data and captured within an integrated model of global change (IMGC) such as GCAM-USA. We will describe the current, ongoing activities to implement this analytical framework, and the initial results we have obtained thus far.

3.1 The disaggregation of residential energy demand

IMGCs tend to be used for macro-scale assessments of energy and environment futures, and often lack the kind of clarity and granularity on the micro-scale influences that we see in Figure 1, above. IMGCs are useful for evaluating how a complex and varied set of drivers can lead to broadly-stated outcomes of market level demand (i.e. supply, trade and prices) – alongside other environmental impact indicators. But the ability to use such an integrated assessment tools for detailed socio-economic impact analysis is limited without making a number of essential, structural modifications.

In this paper we show how an IMGC like the GCAM-USA model can be modified to include a disaggregated representation of household residential demand that is capable of capturing some essential aspects of energy security, across a range of socio-economic classes and types of consumers. This works builds on an earlier assessment of Sampedro *et al* (2021) who used the GCAM-USA model to evaluate how lessening or deepening income inequality affects aggregate residential energy consumption – dividing the aggregate residential energy demand into 5 income classes.

The graphic below shows how the trend in residential energy demand under alternative income distribution scenarios, in their paper – with the richest quintile (Q5) having the highest energy demand in the 'constant' case – but with the poorest one (Q1) realizing the greatest gains, when the income distribution becomes more 'egalitarian' over time.

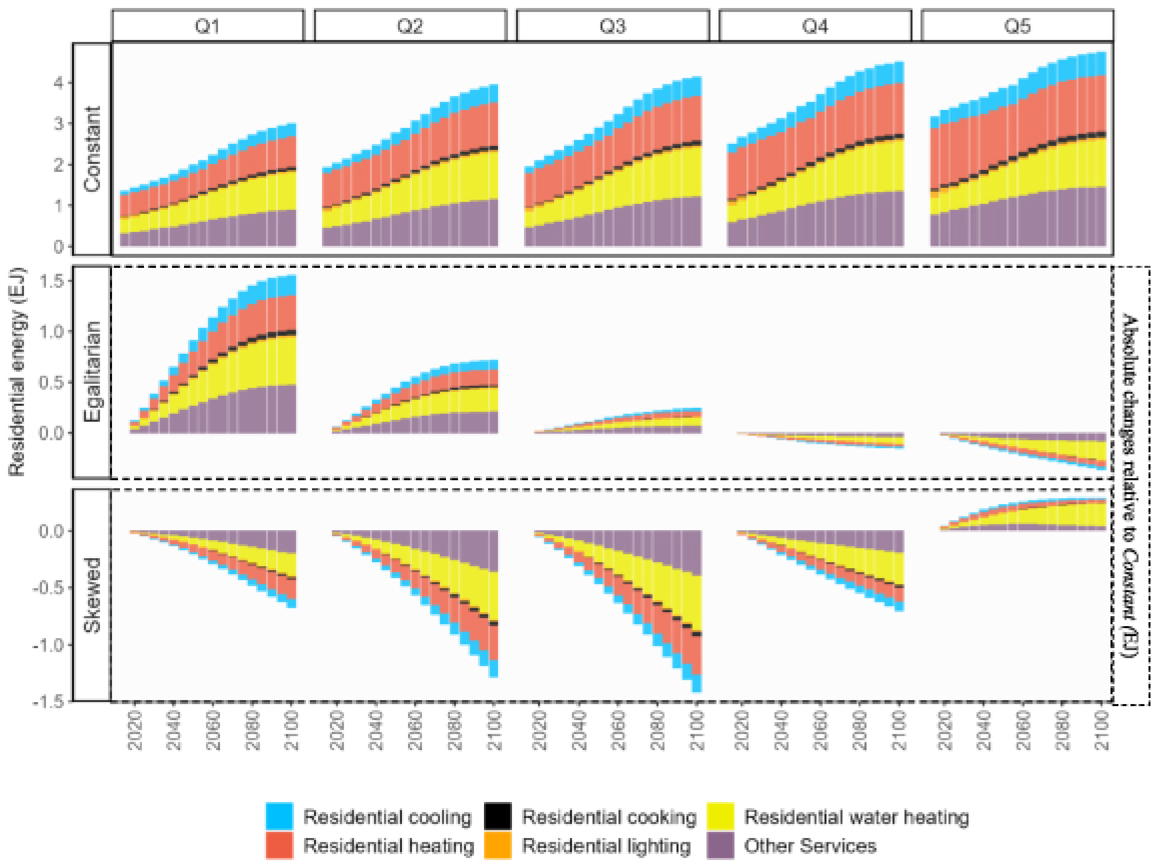

Figure 7. Residential energy demand-disaggregated by service – under alternative cases

[source: Sampedro *et al*, 2021, Fig. 3]

This illustrates the fact that poorer households tend to have un-satiated demand for residential energy, and that they will try and "catch" up in realizing their un-satiated when given more income. The richest quintile, by contrast, is already near satiation – and show a much smaller increase in demand when the income distribution is skewed more in their favor (as shown in the bottom panel for the 'skewed' scenario). These are the characteristic differences in household residential energy demand that we intend to explore further in this work.

3.2 Building in key energy security metrics into GCAM-USA

In this work, we build on the framework used in Sampedro *et al* (2021), and use a finer disaggregation of household residential energy demand across 10 income classes. We also go further to derive measures of energy insecurity that show how deep decarbonization pathways of energy transition might affect various socio-economic classes differently. The particular measures of household energy security that we utilize in this analysis are:

- The share of total household income that is spent on residential energy expenditures
- The degree of satiation of demands for residential energy services

Which we evaluate by income group, across the subregions (i.e. states) of the US, over the projection horizon of the model (2015 to 2050).
The share of total household income spent on energy is a measure of 'energy burden' that is commonly used in the literature (and many policy studies) to capture the degree of fiscal 'stress' that households are under, while trying to meet basic energy needs (Drehobl & Ross, 2016; Eisenberg, 2014). Typically, a household spending more than 6% of its income on energy costs is considered to have a high energy burden – and could be classes as 'energy poor' (Colton, 2011)[1].

3.3 Some preliminary results and plans for further work

To get an idea of how some of the key energy security metrics might evolve across time, within a model like GCAM-USA – we did some preliminary calculations of energy burden. We took the residential energy demand projections from the paper of Sampedro *et al* (2021) and calculated the ratio of residential energy service cost and total GDP, by income quintile – as a proxy for the ratio of household energy expenditures and total household income. In later discussion, we will show how these measures can be improved. But for now, this serves as an approximation of how energy cost burden differs across the different income groups, across all states, and over a long-term projection horizon.

Looking at some of the biggest states within the US – such as New York and Texas, we illustrate how the energy burden might differ across income groups – as is shown in Figure 8 below.

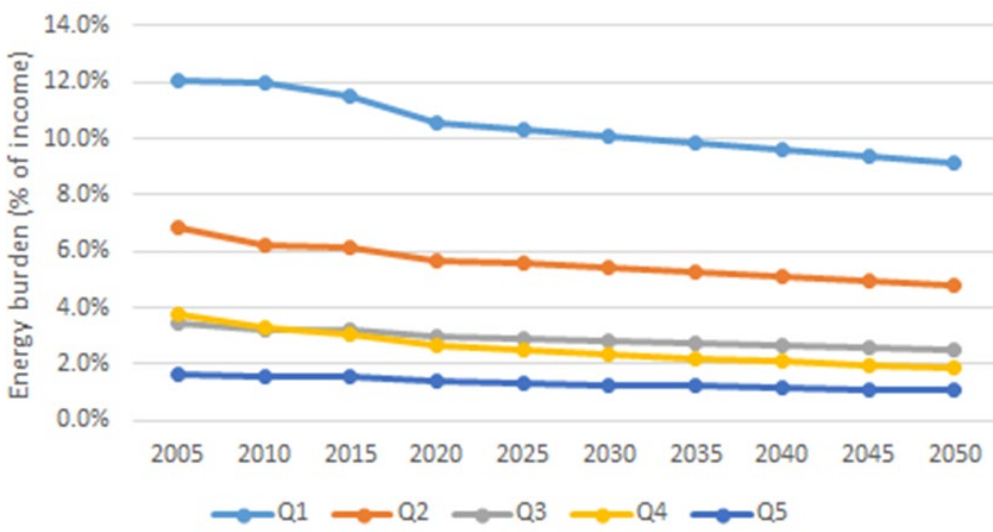

Figure 8. Energy burden by income quintile in New York State, calculated from GCAM-USA projections of residential energy demand

[1] Others define broad ranges of energy burden that households could fall under – with 'energy stressed' households spending between 4-7% of their income on energy; while 'energy burdened' households spend within 7-10% of their income on energy. Those spending more than 10% of income on energy, would be considered 'energy impoverished' (Fisher, Sheehan & Colton, 2003).

In this figure, we see that the energy burden in the lowest income quintile (Q1) is considerably higher than that seen among the others, in the state. The burden of Q1 is almost double that of the next income group (Q2) and over six times that of the richest quintile (Q5). The energy burdens all decline with time, and those of quintile 3 and 4 are very close to each other – and coincide for some periods. Figure 9, below, shows the energy burden trends for the state of Texas.

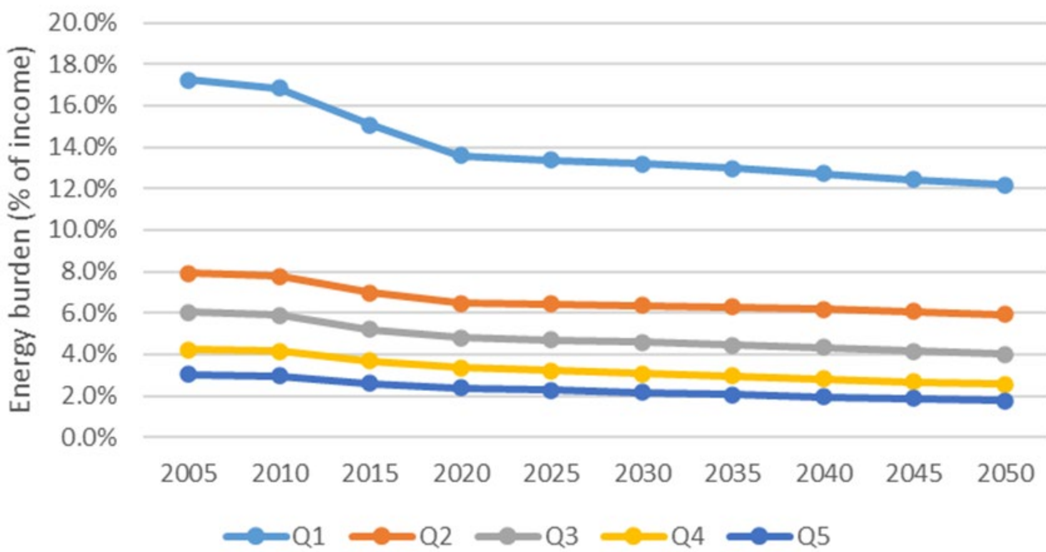

Figure 9. Energy burden by income quintile in the state of Texas, calculated from GCAM-USA projections of residential energy demand

In this graphic, we see that the energy burden of the poorest quintile is a third higher than that seen for Q1 in New York, and is also double that of the next income group (Q2)

The preliminary results that we have shown in Figures 8 and 9 exhibit much higher levels of energy burden than is actually observed in the consumer expenditure data for the US – as we see in the table below (Table 3), which is derived from data collected by the US Bureau of Labor Statistics, and aggregated to the quintile level from the original table (referenced below).

Table 3. Energy burden for the US calculated from 2015 Consumer Expenditure Survey Data (by quintiles of pre-tax income, and aggregated across states/regions)

	All consumer units	Lowest quintile	Second quintile	Third quintile	Fourth quintile	Highest quintile
Mean total annual expenditures	$55,978	$48,949	$70,131	$91,826	$127,340	$221,040
Mean food expenditures	$7,023	$7,534	$10,043	$11,599	$16,329	$24,697
(food share)	12.5%	15.4%	14.3%	12.6%	12.8%	11.2%
Expenditure in energy categories						
Natural gas	$421	$521	$675	$774	$899	$1,343

Electricity	$1,460	$2,026	$2,615	$2,863	$3,229	$3,864
Fuel oil & other fuels	$116	$138	$186	$210	$232	$398
Total energy expenditure	$1,997	$2,685	$3,476	$3,847	$4,360	$5,605
Expenditure share of energy	3.6%	5.5%	5.0%	4.2%	3.4%	2.5%

[source: aggregated from US Bureau of Labor Statistics, Consumer Expenditure Survey 2015, Table 1110]

This table shows, by decile of income, the share of total household expenditure in both food and energy spending, and we note that the mean values (across all regions) for these deciles is substantially lower than what our preliminary results show from Figure 9.

If we look at the US consumption and expenditure data broken out by regions (as we have also done for GCAM-USA results), we also note that the levels of energy burden (aggregated across deciles) is also substantially lower (Table 4) than what we have calculated from our preliminary GCAM-USA based analysis.

Table 4. Energy burden for the US calculated from 2015 Consumer Expenditure Survey Data (by aggregate US region, aggregated across all income groups)

	All consumer units	Northeast	Midwest	South	West
Mean total annual expenditures	$55,978	$58,976	$55,071	$52,020	$61,244
Mean food expenditures	$7,023	$6,882	$7,090	$6,613	$7,776
(food share)	12.5%	11.7%	12.9%	12.7%	12.7%
Expenditure in energy categories					
Natural gas	$421	$687	$599	$250	$324
Electricity	$1,460	$1,345	$1,282	$1,759	$1,209
Fuel oil & other fuels	$116	$352	$103	$55	$41
Total energy expenditure	$1,997	$2,384	$1,984	$2,064	$1,574
Expenditure share of energy	3.6%	4.0%	3.6%	4.0%	2.6%

[source: US Bureau of Labor Statistics, Consumer Expenditure Survey 2015, Table 1800]

The difference arises partly from the fact that the GCAM-USA based calculation is using the GDP values disaggregated to each quintile, whereas the values from the BLS data is capturing actual income values. The other reason for the difference lies in the fact that the BLS data is using actual measured expenditures on energy, whereas the GCAM-USA based calculations use a service cost index that is captured in the model, which drives demand behavior – but doesn't necessarily capture actual spending.

In order to refine these numbers further, we will take the following steps:

- Use the energy expenditures captured in the US Energy Information Agency's Residential Energy Consumption Survey (RECS) data – for each income group – as the base year value, and shift it over time by the same % change as the service cost index, in the GCAM simulations
- Use the projections of household net income (by income group) that will be generated by a separate task of the *GODEEEP* project as the income value, rather than GDP

These, together, will give us a measurement of energy burden that is consistent with data, and which will reflect future state-level trends that are consistent with the forward projections of GCAM-USA.

Aside from energy burden, we could also try to capture how much of each income group's residential energy demand is satisfied – in terms of the level of demand satiation. The degree of satiation will be measured directly from the simulated results of GCAM-USA, given that the model structure has a built-in satiation level for each socio-economic group. So the 'distance' between the actual demand and the satiated demand, for each income group – will be a measure of the un-met or un-satiated demand for that particular group.

Although we would like to get a complete picture of household energy security by including measures of reliability and usability into our analysis – this is currently beyond the scope of what we're able to do within GCAM-USA at present and will be left for further research[1].

[1] some of which is currently ongoing, within the GODEEEP research project of PNNL, with a diverse set of tools, beyond GCAM-USA itself.

4.0 Concluding remarks

The LDRD-funded project that we undertook in the summer of 2021, provided us a means of taking the first steps towards building a coherent framework for evaluating human well-being within a global change modeling framework. In order to reduce the scope of our analysis to something manageable – and which was aligned with the research interests of the lab – we chose to focus on energy security, as a domain of analysis. We have illustrated how a key metric of energy security – namely household energy burden – can be captured within a version of GCAM-USA that has disaggregated residential energy demand across income groups. Though our measure of energy burden, coming from the projected indicators within GCAM-USA was somewhat crude and approximate, we have identified ways in which this approximation can be further improved through better data on household energy usage and spending, and more refined projections of household level income. This, along with other ongoing work, will be part of the larger 'Agile Investment' project (*GODEEEP*), that will develop other energy security metrics beyond energy burden, and which will examine the impact of alternative deep decarbonization strategies upon these well-being indicators.

The other elements of well-being that the summer LDRD project began to map out – across the domains of water and food – will be explored further in future work, and will form part of an evolving effort within JGCRI and PNNL as a whole to better understand the impacts of global change trajectories on human well-being. We believe that these efforts have scientific value to the wider research community, and will help deepen our understanding of potential tradeoffs and synergies that deep decarbonization – and other environmental management strategies – might have on important dimensions of human well-being and socio-economic growth and development.

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Appendix A – The *GODEEEP* project

Here we give a brief overview of the *GODEEEP* project[1], in order to provide the reader with a better understanding of the wider body of work that this summer LDRD activities is currently feeding into.

The *GODEEEP* project – which stands for "Grid Operations, Decarbonization, Environmental and Energy Equity Platform" – is a research effort funded by PNNL to explore the deeper implications of medium- to long-term decarbonization strategies, on the operation and expansion of the US energy system, and upon key aspects of human well-being.

This research effort draws from staff within the Earth and Biological Sciences (EBS) and the Energy and Environment (EE) Directorates of PNNL, and represents an 'Agile Investment' that the lab has made with internal resources, to push forward promising and potentially high-impact research in an emerging field of interest among both scientists and policy makers. The project co-PIs are drawn from those two research directorates, and their key aim is to harness the ongoing strengths in energy systems analysis and the quantification of key human-earth systems interactions with integrated models of global change, within PNNL. Many of the key analytical components of *GODEEEP* are drawn from modeling tools that have been developed within key Scientific Focus Areas of PNNL, such as the "Integrated Multi-sector Multi-scale Modeling" (IM3)[2] program, and the "Global Change Intersectoral Modeling System" (GCIMS) project[3].

The *GODEEEP* project aims to answer the following key research questions:

- How will deep decarbonization force the electricity infrastructure of the US to change, and where might we find stranded assets being located, as a result of this?
- In order to achieve clean grid operations, what kind of energy storage capacity will be needed, and where should it be located?
- What is the value of improving the forecasting of sub-seasonal renewable resource availability, with an aim towards enhancing resilience?
- How will human well-being and equity be affected by deep decarbonization efforts – through various pathways, such as the change in residential electricity rates, the emissions generated by existing and new power plants, employment opportunities and income changes, and the increased access to electric vehicles?

GODEEEP aims to build enduring capacity within the lab for addressing these questions, with a suite of innovative modeling tools that allow:

- The medium- to long-term quantification of energy systems transition under global change, under a range of scenarios
- The integration of global change modeling tools with models of electricity grid operations
- For optimization of energy storage and siting to address uncertainties in the forecasting of sub-seasonal consumer demand and energy resource availability

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[1] See the project website: https://www.pnnl.gov/projects/godeeep
[2] See: https://im3.pnnl.gov/ for details
[3] See: https://gcims.pnnl.gov/global-change-intersectoral-modeling-system for further details

Appendix B – Exploring other well-being domains

During FY21, the research team began to identify potential use cases for human well-being analysis applied to different domains of interest. Water, Food and Energy were considered the best candidates to being exploring and thinking about critical well-being linkages.

Below is a table that lays out the possible sectors/domains, model types and scales of analysis that can be used for empirical analysis of HWB.

Table 5. Potential use cases across different domains of interest, to which the analysis of well-being could be explored

Domain of Application	Metric	Scale	Model type(s)	Possible Region/Case study	Notes
Water	scarcity and/or reliability of water access & supply	household-level	agent-based modeling linked to regional hydrological model with linkages to GCAM outputs	Jordan, US	the US examples are based upon linkages to MOSART-WM with agent-based models of farming calibrated with the PMP methodology -- but this only covers agricultural water use, and not the domestic/hhold use that the Jordan example covers. The metrics of equity, in this case, could be across large/med/small farmers
Food	deviation or 'gap' from target intake/availability of calories (dietary energy) or key macro-nutrients (protein/fiber/etc)	regional per capita average (aggregate macro-level) or on a per-capita level for representative/statistical agent/hhold	post-processing of GCAM-based results with a set of relationships/equations. Could also be applied to a region/country-specific ag market model - driven by outputs from GCAM	for any country/region of choice within GCAM. Or for specific econ market model	
Energy	energy poverty (share of hhold income spent on fuel/energy)	household-level (statistical or representative type within a region)	post-processing of GCAM-based results, making use of RECS data and applying a defined set of calculations/equations	USA	calculating a deviation or 'gap' b/w available/affordable heating/cooling services & those needed for 'minimal' comfort - is appealing, but more complicated to implement. I think the energy demand relationships currently in GCAM are set up in a way that assumes the thermal energy needs are satisfied, and met by the energy system. Currently -- there's no mechanism for price-rationing (i.e. a case where hholds have to reduce demand before the desired HDD/CDD targets b/c of high costs of provision/supply)

The project team laid out the key metrics of well-being that are relevant to each of these domains, and pointed out the type of data that could quantify them, as well as the kind of modeling framework that could carry out forward-looking projections of how these indicators of well-being might change over time, in response to key drivers of global change.

Given the short time that was available to do this initial scoping - before the activities of the *GODEEEP* project commenced in early 2022 – we were not able to do any exploratory quantification along the water or food domains with the metrics, data and models outlined in Table 6, above. Hopefully this will be taken up by PNNL in future research work.

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