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Multi-Variable Parametric Analysis of Prototype Building Energy Performance Using Current and Future Weather Scenarios for Data-Driven Market Transformation Support

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Energy and Transportation Science Division

MULTI-VARIABLE PARAMETRIC ANALYSIS OF PROTOTYPE BUILDING ENERGY PERFORMANCE USING CURRENT AND FUTURE WEATHER SCENARIOS FOR DATA-DRIVEN MARKET TRANSFORMATION SUPPORT

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August 2022

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ABSTRACT

This project aimed to develop a public building simulation data set that may be used to inform building code development and guidelines for building innovation. The data set consists of several common building types and many representative locations across the United States. A parametric design of building properties was developed to create a range of building energy models that represent common building design decisions with a particular focus on fenestration options. The US Department of Energy prototype building energy models were altered according to a parametric building design and simulated using both current weather data and future weather estimates derived from global climate models. The resulting data set allows for pertinent exploration of building design parameters, including fenestration, within different environments across the United States in the broader context of climate change.

1. STATEMENT OF OBJECTIVES

1.1 MOTIVATION/BACKGROUND

Code adoption of improvements in building envelope energy efficiency are often hindered by the lack of reliable and meaningful data. Modern building energy analysis tools can assess the energy performance implications of several individual variables, but combinatorial (or holistic), non-siloed analyses are rarely considered in code and standards development.

Using windows as an example for all envelope innovations, traditional silo analysis has slowed market transformation to higher performing products. Advances in window insulating value are limited by double pane glazing. Low-emissivity coatings, inert gas fills, warm edge spacers, and improved frames have now taken this double-glazed system to its energy performance limit. The next steps in increasing insulating value will require investments in new technologies, such as triple glazing, vacuum glazing, and aerogels. The effects on whole building performance, occupant comfort, equipment sizing, power demands, and other derivative benefits are neither readily captured nor available to either justify investment or support rapid market transformation.

Cardinal Glass Industries now seeks to deliver the next generation of glazing innovation to the industry supported by whole building energy and comfort analysis for multiple locations across the United States. Also, as building life expectancy often exceeds 100 years, there are concerns that current energy modeling tools using historical weather data may be insufficient to properly assess many window and glazing innovations in the context of their effects on future building performance.

The US Department of Energy's (DOE's) Oak Ridge National Laboratory (ORNL) is ideally positioned to assist in answering numerous critical building energy performance questions because of its vast energy modeling experience, current research on various future weather scenarios, state-of-the-art computer tools, and statistical analysis expertise.

Together, ORNL and Cardinal Glass have conducted an innovative research project that will help answer questions of building envelope and whole building energy performance, helping shape critical building efficiency decisions for years to come. A new precedent has been established for collaborative research with DOE, ORNL, and others in the building industry to expand upon and improve the community's collective understanding of comprehensive building performance.

2. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

The DOE's mission is to ensure the security and prosperity of the United States by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions. The Building Technologies Office's mission is to develop, demonstrate, and accelerate the adoption of cost-effective technologies, techniques, tools, and services that enable high-performing, energy-efficient, and demand-flexible residential and commercial buildings in both new and existing buildings markets. Both of these missions support an equitable transition to a decarbonized energy system by 2050, starting with a decarbonized power sector by 2035, and both are a focus in this work.

To best understand how to transition toward a decarbonized energy system in the future, it is important to understand how the built environment will react to changing climate conditions. Developing weather data based on global climate models that may be used in building energy modeling is a useful step in this process. This study furthered this research by simulating with future weather data a subset of building energy models representing the majority of the built environment. This study compared these future weather simulations to current simulations to evaluate how different combinations of building properties coupled with climate change will affect building energy use in representative cities across the United States.

3. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

3.1 PARAMETRIC EXPERIMENTAL DESIGN

When selecting building design parameters for evaluation, selecting common yet generalizable design variables was important. Therefore, the most common residential and commercial building types were chosen, and locations were selected based on representative cities for each climate zone to understand the impact of future weather in all areas of the country. Several other performance-related variables were included to better understand how these variables react when coupled with various window technologies and environments.

From the perspective of analyzing windows, there are nearly 50,000 variations of window parameters across 11 categories of building characteristics. Given the wide range of window options available, initial regression analysis was conducted to minimize the number of window options while retaining sufficient resolution to accurately address available products. Window heat loss is expressed by the U-factor ($W/m^2 \cdot °C$) and represents a whole window value (glass and frame). Presuming nonmetal framing, the range of U-factors by glass type are listed in Table 1.

Table 1. U-factor by glass type

Glass type	U-factor (approximate value in $W/m^2 \cdot °C$)
Single pane	6.0*
Double pane	3.0
Double pane with low-E glazing	2.0
Triple pane with two low-E glazing	1.0

*The marketplace understands that single-pane windows are inadequate (too cold in winter, too hot in summer), so available options for this analysis are capped at a U-factor of 3.0 $W/m^2 \cdot °C$.

A window's solar heat gain coefficient (SHGC) can vary from 0 (no gain) to 1 (100% gain). SHGC is dimensionless, and when the frame is included, it can have values as listed in Table 2.

Table 2. Solar gain and SHGC ranges

Solar gain	SHGC
High	0.50
Medium	0.30
Low	0.10

The energy cost trends for the building with a 3 U and 3 S data set are shown in Figure 1. The error on the curve fit to the full 21 U and 26 S data sheet ranges from −0.2% to +0.3%, which is more than adequate to support results from a 9-point simulation set. This range drastically reduces the number of window-based parameters necessary. The full parametric matrix containing combinations of all building design variables and values to be simulated is shown in Table 3.

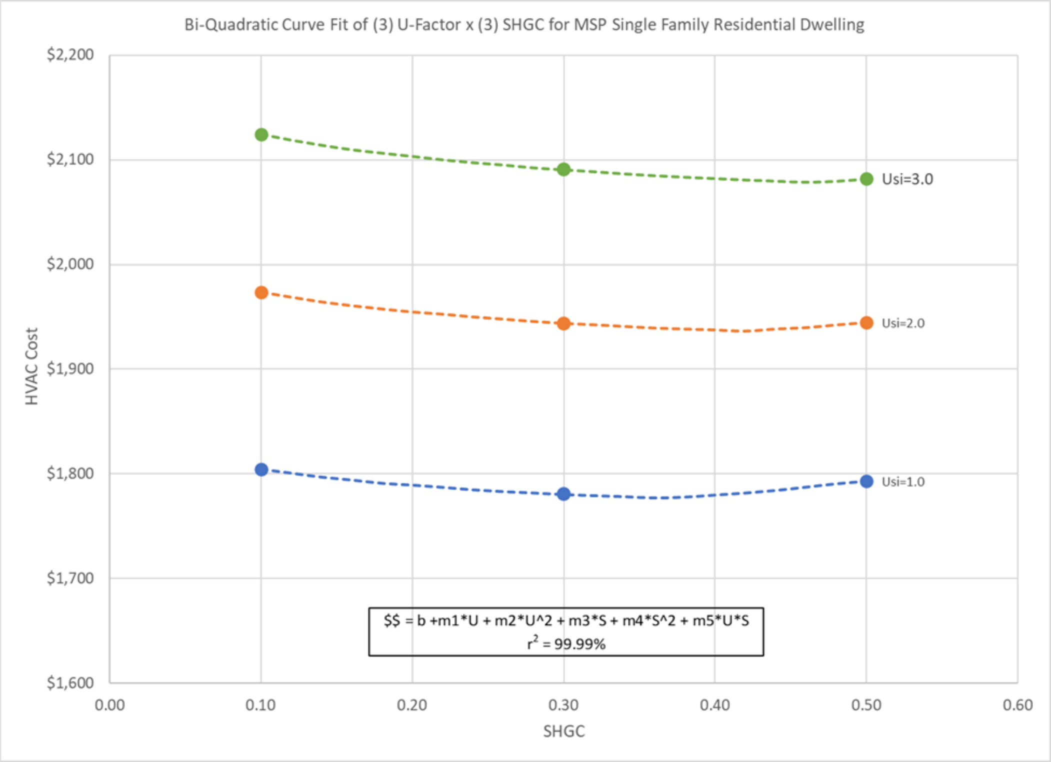

Figure 1. Window parameter selection validation. The solid data points are the actual simulation, and the dashed line is a biquadratic regression of the 9 points.

Table 3. The parametric sampling values were selected for common building types and building properties, resulting in an initial set of 23,328 and final set of 467,856 unique building simulations Representative cities are shown with climate zone in parentheses.

Sampling Parameter	Inputs		Sampling Parameter	Inputs
Building Types	Single-family (Gas/HP)	Small Office	Window U-factor	1
	Multi-family (Gas/HP)	Medium Office		2
	Apartment Mid-rise			3
Vintages	2004/2006		Window SHGC	0.1
	2018/2019			0.2
	Future			0.3
Locations	Miami (1A)	Seattle (4C)	Window to Wall Ratio	0.1
	Houston (2A)	Chicago (5A)		0.2
	Austin (2A)	Des Moines (5A)		0.3
	Phoenix (2B)	Denver (5B)		0.4
	Atlanta (3A)	Minneapolis (6A)	Orientation	North/south
	Oklahoma (3A)	Helena (6B)		East/west
	Las Vegas (3B)	Duluth (7)	Window Distribution	Equal
	San Francisco (3C)			North/south 50/50
	Baltimore (4A)			East/west 50/50
	Topeka (4A)		Air Leakage	Default
	Albuquerque (4B)			Improved 50%
Weather	Typical Meteorological Year (TMY3)		HVAC Efficiency	Common
	Future Typical Meteorological Year (fTMY) (SSP585)			High

3.2 FUTURE TYPICAL METEOROLOGICAL YEAR WEATHER FILE DEVELOPMENT

The Intergovernmental Panel on Climate Change created Representative Concentration Pathways (RCPs) to standardize the work of many climate researchers around the world and explore how different levels of emissions would affect the global climate. These pathways were defined by the amount of radiative forcing (W/m^2) expected in a scenario through 2100 (Hausfather 2018). Four scenarios range from a high-mitigation, low-emission scenario (2.6) to a low-mitigation, high-emission scenario (8.5). Figure 2 shows the various amounts of radiative forcing between the scenarios until 2100.

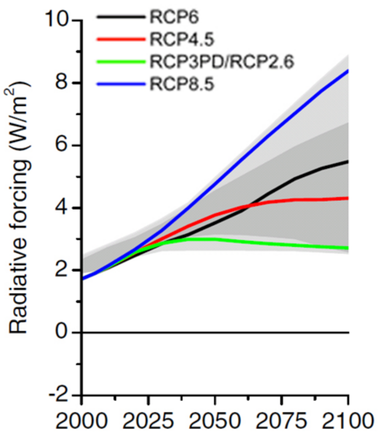

Figure 2. The RCPs represent scenarios based on the amount of radiative forcing by 2100. These scenarios correspond to emissions rates and climate policy (Lachance-Cloutier et al. 2015).

Shared Socioeconomic Pathways (SSPs) build upon these RCP pathways to include socioeconomic variables to better understand how these factors will impact the global climate. These narratives provide baseline possibilities of different future socioeconomic pathways that allow researchers to understand what variables affect climate and how climate change mitigation can be achieved in these possible future scenarios. The SSPs are illustrated in Figure 3.

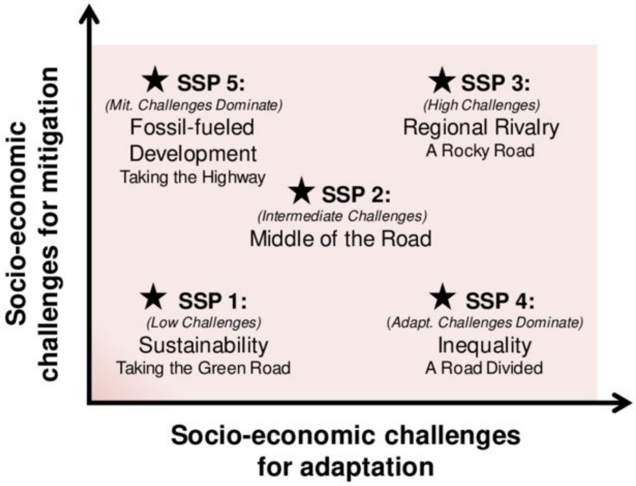

Figure 3. The various SSPs provide different baseline scenarios for future years, from which climate analysis may be conducted. O'Neill et al. 2015.

The RCPs combine with the SSPs to create a baseline future socioeconomic scenario based on the SSP with climate policies imposed by the RCPs to gather a future overall scenario. SSP585 (SSP 5, RCP 8.5) is a scenario based on fossil-fueled development with high levels of economic growth and low mitigation by policymakers. This scenario was evaluated for this analysis because it provided an extreme carbon emission future that can be compared with today's rates to understand how climate change will affect building energy across the United States. The true emissions scenario is likely lower, but using the maximum showed the full effect of climate change in different climate zones in the United States.

Downscaled Coupled Model Intercomparison Project 6 (CMIP6) data were used for this analysis. The data needed to be downscaled temporally because the building simulation engine used for this analysis

(EnergyPlus) requires hourly weather data. The data had to be downscaled spatially because this project requires a city-based analysis, in contrast to the gridded nature and raw spatial resolution of the climate models that resulted in grid points that landed on naturally occurring physical phenomena, such as mountains, valleys, or bodies of water. Downscaling the data allowed for the selection of a point in the city that was comparable to the measured data from that city. The downscaling was accomplished using a regional climate model system (REGCM4) and a double bias correction constructed analogues method, as well as measured data from the Livneh and Daymet meteorological data sets for statistical training and bias correction (Rastogi et al. 2021).

Typical meteorological year (TMY) is a type of weather data that contains a year of hourly data that best represents the median monthly weather conditions over a multiyear period. This data type was used as the measured data baseline for each US city. Many researchers employ the use of individual future years to estimate climate change, but it is more defensible to construct a more representative, single-year weather pattern from 18+ years of data. This representation of a multiyear period was applied to future years, limiting single-year variability and outliers. This process used the Sandia method and Wasserstein distance on weather statistics for dry bulb temperature, dew point, wind speed, relative humidity, and direct radiation to select a representative month for each month of the multiyear period (Wilcox and Marion 2008). The resulting weather data are a 12-month period of months that were selected for being closest to typical. The TMY process methodology was altered and used to work with CMIP6 climate model weather data for each individual location. This study employed an approach that generated a future typical meteorological year (fTMY) weather file for each city for two future 20-year spans (2020–2040 and 2040–2060).

3.3 BUILDING ENERGY MODEL DEVELOPMENT AND SIMULATION

Building energy was estimated in this analysis using EnergyPlus, DOE's flagship whole building energy simulation program. EnergyPlus is an open-source and broadly supported building simulation tool that practitioners, researchers, and others use to model energy consumption of a building based on a set of characteristics describing the building. A carefully curated set of EnergyPlus building energy models, Prototype Building Models are used for codes and standards determinations. These DOE prototype buildings represent common buildings in the United States, with properties of these models gathered from surveys of existing buildings and using standard rule sets from building codes and standards. Each of these prototype buildings has a set of vintages that represents various construction years and contains different levels of technology and efficiency. The commercial prototype buildings cover 75% of commercial building floor area in the United States across all climate zones (Office of Energy Efficiency and Renewable Energy).

In total, 112 DOE prototype models were used to start this analysis. This analysis examined five building types, two vintages, and eight climate zones. For the residential building types (single-family and multifamily), a model with a gas furnace and a model with a heat pump were used. These models were copied several times according to the number of combinations a particular building model would employ based on the parametric sampling (Table 3) and relabeled with a specific ID. This resulted in 155,953 prototype building energy models. Next, the model properties were edited according to the building properties associated with each unique ID using a parallelized Python script and the library EPPY (eppy.readthedocs.io/), a Python library built to aid in the editing of EnergyPlus models. These unique models represented combinations of each building property in the parametric sampling and could be simulated to estimate the effect of each of these variables. The models were simulated using the TMY3 weather file associated with each location, as well as two fTMY files (2020–2040 and 2040–2060).

3.4 RESULTS AND ANALYSIS

This work has resulted in a final data set of 467,856 building simulations that can be used to evaluate building designs across the United States and in the context of climate change.

A common analytic approach characterizes the relationships among building properties and their interactive effects that determine building energy use. Figure 4 shows the correlation between the building design parameters and building energy use in Topeka, Kansas. For this comparison, categorical variables were converted to ordinal integers. Building type and window distribution had the strongest correlations between a building design parameter and building energy use. Building type had a notable correlation because the equipment, occupancy, and loads of different building types affect building energy usage. The window distribution shows the importance of placing windows with proper characteristics for specific surfaces of the building. Meanwhile, window-to-wall ratio had a notable correlation because a typical window lets in and out approximately 10 times more heat than the average wall. The more window area a building has, the more energy the building will likely use.

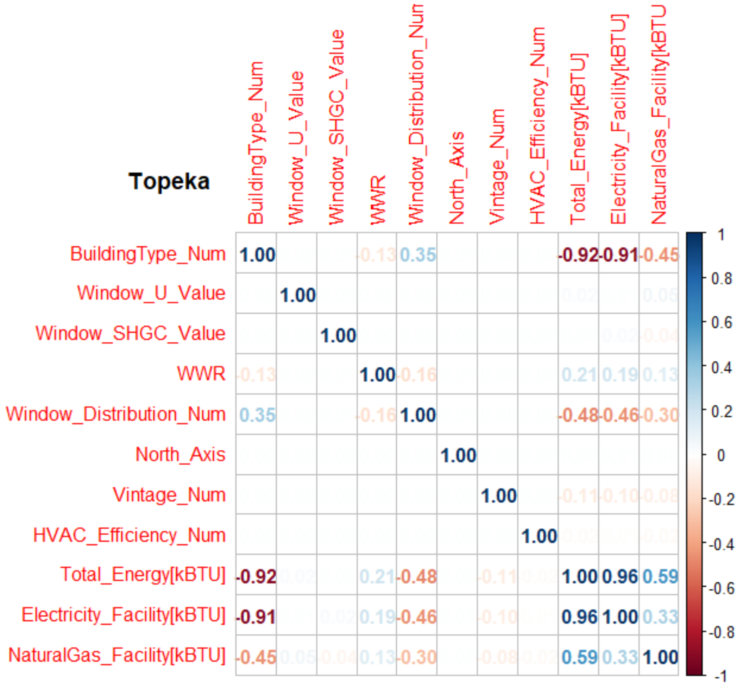

Figure 4. Correlations between building design parameters and building energy use in Topeka, Kansas. Building type and window distribution had the most significant impact on building energy use. Values close to 1 indicate a strong positive correlation while values close to -1 indicate a strong negative correlation. The "Num" value indicates the variables was converted from a categorical to an ordinal variable for comparison.

An analysis was conducted to understand and characterize how future weather is likely to affect building energy use. Figure 5 shows total building energy use of each building type for a sample of climate zones across the United States. The predicted rising future temperatures led to an expanded average difference between the ambient temperature and the typical building set point in warm climates, and a reduction in the average difference between ambient temperature and building set point in cold climates. This change, caused by general temperature increase, led to an increase in building energy use in warmer climate zones in future years and a decrease in building energy use in future years in the coldest climate zones.

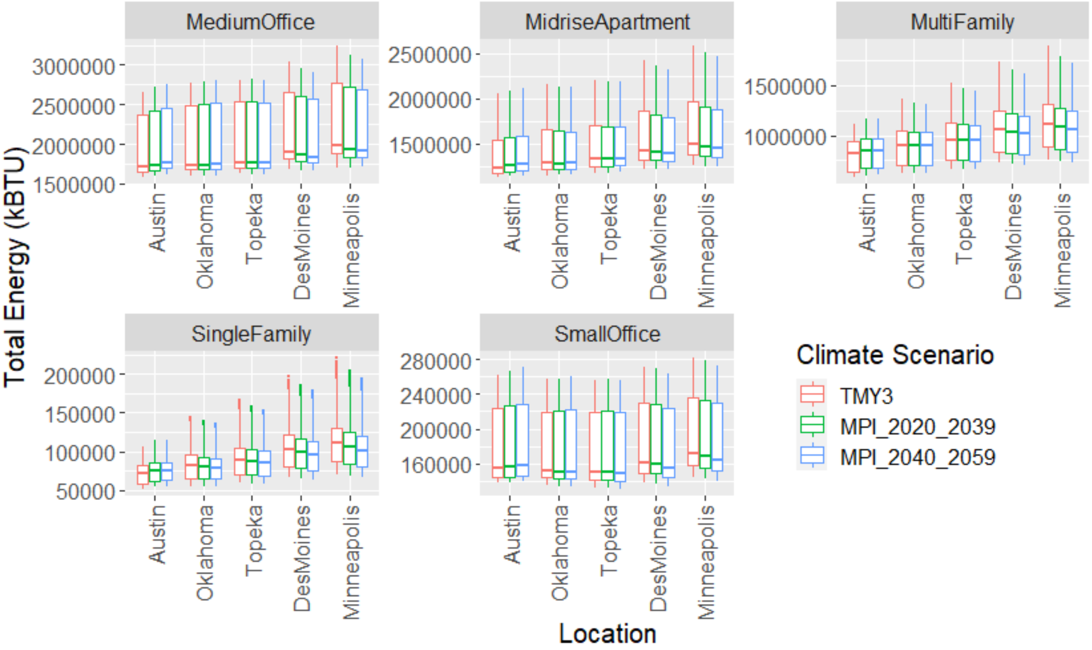

Figure 5. Typical weather (TMY3) and predicted climate change and weather (fTMY; 2020–2040 and 2040–2060) effects on building energy use for each building type at a sample of southern to northern US locations. The data for this Figures was derived from the Max Plank Institute (MPI) global climate model.

4. SUBJECT INVENTIONS

Two primary subject inventions have been developed as a part of this work. First, future weather data files were derived from Intergovernmental Panel on Climate Change climate models. These 214 hourly future weather files from 18 cities and 2 sets of future years (2020–2040 and 2040–2060) can be used for building energy analyses through simulation in EnergyPlus with any EnergyPlus building energy model. This allows for considerable future analyses in these selected cities. Second, the simulation data set consists of the input building properties and simulation outputs. This type of data set allows for many different analyses and provides answers to questions regarding possible future scenarios, a few of which have been addressed in the current results.

5. COMMERCIALIZATION POSSIBILITIES

Although the initial objectives of this project included identifying future building and energy code priorities regarding window performance, the research approach taken has led to several other potential market transformation opportunities. These include the following:

- A framework for local and national policy development focusing on improving building energy efficiency
- A tool to help provide locally specific guidance for considering building and window performance priorities under likely future weather conditions
- A tool to help provide locally specific guidelines on window performance optimization for new and existing construction

5.1 A FRAMEWORK FOR LOCAL AND NATIONAL POLICY DEVELOPMENT FOCUSING ON IMPROVING BUILDING ENERGY EFFICIENCY

Change to building energy codes is difficult, time intensive, and often made with little to no data upon which to make a specific proposal—especially for something as complicated as windows. Now, through this Cooperative Research and Development Agreement (CRADA), a framework has been established to provide meaningful and actionable window energy performance targets, applicable to multiple building types, for building codes across the United States. Whole building energy performance data can now be easily generated for specific states and localities, as well as for broad code-defined climate zones. This data set and analysis demonstrates proof of concept for a tool whereby window performance priorities could be easily established for minimum energy codes everywhere, as well as for high-performance (i.e., stretch) energy codes.

The 18 locations and 5 building types evaluated showed a degree of performance granularity rarely presented to building energy code decision-makers. We hypothesize that this approach—employed on a local scale or expanded to include hundreds of US locations—could provide window performance feed stock for years to come.

The market transformation potential is evident. Improved window performance factors in codes could be more easily adopted because of the presence of the CRADA data. An improved user interface to help navigate the results from the (necessary) expanded data set (e.g., more locations, more building types) would be needed. Through these data, local and national code officials could have easily accessible location-specific data with which to establish new building energy use standards.

These data could also be used to help set new targets, especially regarding key decision-making indices such as consumer cost, source energy, and atmospheric pollution. For example, what is the best window U-factor and SHGC technology for Tampa? What about for Topeka or Tacoma? What if the priorities are atmospheric pollution mitigation or state utility program planning? These tools and data can provide valuable and actionable window and building envelope performance targets to address diverse regulatory needs.

Similarly, existing market transformation programs, such as ENERGY STAR, Passive House US, LEED, and others, would now have window and whole building performance data with which to set more fine-tuned window performance targets for such market transformation programs.

Expansion of this data set and experimental design a high priority, as described in Section 6. Should DOE wish to support these objectives, the CRADA team engaged herein would continue to expand these efforts in support of better window and whole building energy codes.

5.2 A TOOL TO HELP PROVIDE LOCALLY SPECIFIC GUIDANCE FOR CONSIDERING BUILDING AND WINDOW PERFORMANCE PRIORITIES UNDER LIKELY FUTURE WEATHER CONDITIONS

The minimum code priorities discussed in Section 5.1 could include informing codes and energy programs about the effect of windows (and other elements) under various future weather scenarios. Current codes have yet to employ forward-focused structures with which code norms are established.

Under this CRADA, the potential exists to inform consumers, builders, policymakers, utility program administrators, and others on how to better prioritize windows and other building energy components when considering the likely future weather that building will face.

As building energy models are exercised and driven with current and future weather data, they can provide local and national decision-makers with a valuable tool with which to determine target performance standards. Projections could be made at various scales, such as 50, 75, or 100 years.

As stated previously, such an objective would require expansion of the data set and analyses to a more granular list of locations. Evaluating other building elements using these techniques would require further parameter expansion. Again, such an effort is a high priority for future collaboration, as mentioned in Section 6.

5.3 A TOOL TO HELP PROVIDE LOCALLY SPECIFIC GUIDELINES ON WINDOW PERFORMANCE OPTIMIZATION FOR NEW AND EXISTING CONSTRUCTION

Although code professionals and policymakers can benefit by using these data and analyses (and related future efforts), consumers making specific product decisions for their homes and offices can use these research results to have the greatest long-term market transformation effect.

Currently, consumers have few tools with which to assess the efficiency priorities of their home readily, easily, and accurately. Broad efforts are limited in their ability to provide locally specific priorities. However, applying these analytical techniques to a larger data set could easily create the needed support for a consumer-focused tool to identify local energy, cost, and pollution prevention priorities.

An expanded data set and regressions, accompanied by a more consumer-focused front end, could enable smarter consumer decision-making on questions such as, “What retrofits to my home will give me the greatest energy cost savings where I live?” Questions such as these could be addressed with a hyper-local focus, including local utility fuel mix and costs to yield a locally relevant set of priorities.

This approach is not limited to windows and window performance. Although the initial CRADA focused on windows, opaque envelope, HVAC efficiency levels, and a few other variables, the approach could be applied even more broadly.

These techniques, when applied to multiple building types, could also help designers better assess long-lived elements such as building envelope components versus shorter life expectancy energy-using components. Investors and lenders could better assess project viability and value versus its design intent. Carbon traders could better assess a project’s pollution prevention capability and trading value.

Different consumer interests could be addressed as easily as a pull-down menu. Users could select from among the 18 Pacific Northwest National Laboratory building prototypes, which cover almost 75% of the building inventory (Office of Energy Efficiency and Renewable Energy). Knowing the building vintage (new or existing) and primary focus (e.g., energy costs, carbon), users could have a ready decision on products, performance, and variables contributing the most to each consumer’s primary focus.

6. PLANS FOR FUTURE COLLABORATION

Several opportunities for future collaboration and the potential second phase of this work are being considered. Current results are shown to be valuable and are highly influenced by location. Adding more locations would allow for the integration of more localized energy costs and grid generation mixes. Energy costs and grid mixes, which affect carbon emissions, can vary greatly by location. Along with more locations, more climate model scenarios (SSPs, RCPs) can be evaluated in addition to SSP585.

Adding more SSP and RCP scenarios would better represent the range of possible future socioeconomic and climate policy scenarios. Adding more building types would also lead to a better understanding of how different building equipment, building shape, building occupancy, and more will be impacted by future energy use. The current analysis only included 5 building types, but up to 20 building types could be considered.

7. CONCLUSIONS

In this work, Cardinal Glass (a leader in the glass and window industry) and ORNL (a leader in building energy modeling) collaborated to develop a data set that can be used to answer prominent questions about building envelope and fenestration. With buildings often lasting more than 100 years, it is important to understand how buildings that are currently being built will handle future weather. A variety of building design parameters (e.g., window properties, building orientation, building age) were selected and implemented in building energy models of some of the most common building types to further this understanding. These parameters were evaluated for 18 cities across the United States that represent different climate zones. Future weather data to be used in the building energy model simulations were developed from Intergovernmental Panel on Climate Change and CMIP6 global climate models. The climate model data were downscaled to a higher spatial and temporal resolution using a novel method developed by Rastogi et al. (2021). The future weather data were formatted into a TMY format to create fTMY weather data that reduced single-year bias and provided a representation of a series of future years. In total, more than 450,000 simulations were run in 3 time periods: the TMY3 period (19762005) and two fTMY periods (2020–2040 and 2040–2060).

The data set resulting from this work spans every climate zone in the continental United States and presents most significant building design decisions for common building types. This data set can be used to set policy and determine which building technologies should be incentivized. Furthermore, it can inform industry as to what material properties should be used in buildings constructed in a climate-aware context.

8. REFERENCES

Hausfather, Zeke. 2018. “Explainer: How ‘Shared Socioeconomic Pathways’ explore future climate change.” Carbon Brief. Accessed July 15, 2022. https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/.

Lachance-Cloutier, Simon, et al. 2015. *Hydroclimatic Atlas of Southern Québec, The Impact of Climate Change on High, Low and Mean Flow Regimes for the 2050 horizon.* Québec: Centre d'expertise hydrique du Québec.

Office of Energy Efficiency and Renewable Energy. n.d. “Prototype Building Models.” Building Energy Codes Program. Accessed July 15, 2022. https://www.energycodes.gov/prototype-building-models.

O'Neill, Brian, et al. 2015. “The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century.” *Global Environmental Change* 42. http://dx.doi.org/10.1016/j.gloenvcha.2015.01.004.

Rastogi, Deeksha, et al. 2021. “How may the choice of downscaling techniques and meteorological reference observations affect future hydroclimate projections?” American Geophysical Union Fall Meeting. https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/890093.

Wilcox, S., and W. Marion. 2008. *Users Manual for TMY3 Data Sets.* NREL/TP-581-43156. Golden, Colorado: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy08osti/43156.pdf