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Vulnerability to climate change impacts of present renewable energy systems designed for achieving net-zero energy buildings

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ABSTRACT

There are high hopes and expectations in the potential of Net-Zero Energy Buildings (NZEB) to contribute to combat the adverse environmental effects from intensive human activity, including energy use. An important related question that has received insufficient attention and is therefore addressed in this study, is how NZEB equipped with renewable energy (RE) systems would perform in future climates that will be caused by the ongoing environmental impacts. In this research, downscaled future hourly weather data from the Global Climate Models (GCM) are used to predict future performance of RE systems for low energy using residential buildings in 10 different climate zones in the U.S. Renewable energy systems with different configurations of Photovoltaic (PV) solar energy and wind system power generation are modeled and coupled with hourly building energy loads. The research results show that buildings with the present configurations of RE will be losing their capability to meet the zero-energy goal in half of the considered climate zones. It was found that the RE systems for a future NZEB should be resized and reconfigured to accommodate climate change impacts. RE systems prioritizing PV systems shows good stability and performance in power generation under expected future climate conditions. A criterion was developed to assist a proposed grid search method for finding the RE system configurations for future NZEB that would identify vulnerabilities of present NZEB's performance under climate change.

1. Introduction

Energy consumption in building is very important considering its large share of the US total energy consumption. In the US, buildings consume 41% of the total primary energy use in the US, and about 50% of the total building energy is used for heating and cooling [1]. To counteract the global climate change (GCC) trend [2], the concept of "net-zero energy buildings" (NZEB) is being studied and to small extent already implemented to reduce the use of fossil fuels, which is the most important contributor to GCC, but also to reduce building energy use in general. While NZEB is expected to play an important role in combating GCC in the future, the climate is changing and our standards for defining, designing and operating the buildings under current NZEB definitions may not be satisfactory for NZEB under future conditions imposed by GCC. The question addressed in this study is whether the NZEB that was designed and constructed today based on historical weather data representing the outer climate environment is still going to function as "zero-energy" in the future, focused on different US climate zones.

Some studies discussed in the following, had been conducted on the impact of GCC on building energy consumption worldwide. Xu conducted research together with the Lawrence Berkeley National Laboratory (LBNL), studying the impacts of GCC on building heating and cooling energy patterns in California [3]. The results show that under the Intergovernmental Panel on Climate Change (IPCC) most likely carbon emission scenario (A2), cooling electricity usage will increase by about 25% and the aggregated energy consumption of all buildings, including both heating and cooling, will only increase slightly since the decreasing building heating load may counteract the increasing building cooling load in most areas of California. In Australia, Wang et al. evaluated the heating and cooling energy requirements and the corresponding carbon emissions of residential houses under different future climatic conditions [4]. By incorporating the future GCC into an existing meteorological weather files, future hourly weather data were constructed. It was found that the carbon emission of a 5-star house was projected to

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have an average increase of 30% in Darwin, 15% in Alice Springs and 19% in Sydney. Radhi evaluated the potential impact of GCC on the United Arab Emirates residential buildings regarding CO_2 emissions [5]. In this research, the design of building envelope and fenestrations in the future is highlighted for combating the increase of building energy consumption as well as CO_2 emission, while Shen and Lukes (using TRNSYS and eQuest modeling) estimated that the GCC will lower the energy efficiency of ground source heat pump (GSHP) systems that currently have high energy efficiency for residential building applications in the US, because the warmer ground in the future will cause an average rise of about 2–3 °C in the inlet and outlet water temperatures of GSHP during the cooling season [6]. Researchers from China also evaluated the GCC's impact on regional renewable energy (RE) systems and found that extreme events (like rainstorms, frost etc.) and the variation of climatic conditions will have substantial impacts on RE in different provinces of China: Guangdong, Gansu, and Tibet were predicted to be the most vulnerable to GCC in terms of RE system installation [7]. Summarizing, it is agreed that future building's energy use and its performance is made complex by the highly potential future change in global climate.

Nonetheless, little research on the influence of future GCC on NZEB was conducted. Robert and Kummert [8] developed hourly future climate data to evaluate if the existing NZEB in Canada will miss the net-zero target for most of the future years in Montreal and they found that the target would be nearly met, and concluded that climate-sensitive buildings such as NZEBs should always be designed using multi-year simulations with weather data that take GCC into account. Such research is not intense, however, especially in US climate zones. In this paper, we will try to understand the GCC impact on US climate as related to evaluating its influences on achieving NZEB performance in the future.

Despite the fact that NZEB has become a familiar term in the buildings field, there are still different definitions and standards of NZEB. There are some currently popular green building standards, including LEED [9] and BREEAM [10]. These standards are more focused on "green" than "zero-energy", and broadly cover the wide context of green buildings. The International Living Future Institute led a Living Building Challenge program which provides Net Zero Energy Building Certification for green living buildings, but strict and scientific definition of what a NZEB is has not been clarified and provided unequivocally. The major reasons for the ambiguity about NZEB are due to [11]: (1) the metric of the energy balance, (2) the balancing period, (3) the type of energy use included in the balance, (4) the type of energy balance, (6) the connection to the energy infrastructure and (7) the requirements for the energy efficiency, the indoor climate and in case of gird-connected NZEB for the building— grid interaction. The definition of the NZEB in this paper is discussed further below. Studies on existing and proposed definitions of NZEB can be found in Refs. [12–15]. Though NZEB does not have a universally acknowledged definition at present, a NZEB is usually defined as a building that achieves annual balance between energy use and generation [16,17].

Hernandez and Kenny stated that the full life cycle of the building could be more appropriate period for the energy balance. By applying this balancing method it is possible to include not only the operating energy use, but also the energy embodied in the building materials, construction and demolition and/or technical installations and thus evaluate true environmental impact of the building [18]. Srinivasan et al. also presented a more sophisticated and information-intensive way of evaluating the concept of NZEB using the emergy which extends the concept of "embodied energy" to the material formation cycle and to its life time. This method and process requires a fully developed emergy database with renewable resource use to assess if a building achieves "lifetime emergy balance" [19]. The understanding of the GCC impact on future NZEB building performance when integrated with renewable systems energy remains, however, not clear enough and needs much more research.

When it comes to the research of different energy balance definition of NZEB, Canada Mortgage and Housing Corporation (CMHC) has led the "Equilibrium Sustainable Housing Demonstration Initiative" which is aimed at helping local teams to design and build 15 net zero energy homes throughout Canada [20]. Instead of using the wording "zero-energy building", CMHC took the word "equilibrium sustainable housing", which means homes that combine resource and energy-efficient technologies with RE technologies to reduce their environmental impact. These houses are actually on-grid "equilibrium sustainable housing". There are two types of net zero-energy building in terms of their relationship to the grid. Off-grid NZEB, which is not connected to a utility grid and hence needs an energy storage system such as batteries or thermal storage, does not get much attention from the government, industry or academia because most of the buildings are not isolated and often located in an environment where other buildings exist, meaning that a grid which provides energy resource (electricity, gas, biomass) centrally and distributes energy to end users is there anyway. Such off-grid buildings are also called "zero stand alone" buildings [21]. The other one, called on-grid NZEB, also known as 'net-zero energy' - 'grid connected' is connected to one or more energy infrastructures such as electricity grid, district heating and cooling system, gas pipe network, biomass and biofuels distribution networks. The scope of NZEB considered in our paper refers to the latter one, the 'grid connected' NZEB because it is more possible to promote in the market, considering its interaction with the grid and its higher potential to realize net zero-energy with the help of the grid assistance in its peak of energy consumption. It has higher potential for achieving NZEB in large scale instead of scattered self-sustained NZEB in suburban areas.

We focus on evaluating the energy performance of the NZEB defined based on the annual energy balance of the building and its RE system during its operation period. The climate change impact on present days' NZEB has not been studies with high granularity by means of hourly building simulation and renewable energy system simulation. In this research, we conservatively assume a NZEB coming into use at least 50 years from now, according to the research conducted by Aktas and Bilec that indicated that the average residential building lifetime in the U.S. is currently 61 years and has a linearly increasing trend [22]. The metric of the balance mainly refers to the source energy balance taking into account the different types of on-site primary energy (electricity demand and thermal heating demand). In addition, for this type of the balance, besides the energy supplied to the NZEB by the grid, we also consider the energy generation from onsite RE systems including photovoltaic, wind, and solar heating panels. The energy balance and the qualification as NZEB is achieved if the overall energy delivered to the building from the utility grid is offset by the overall energy fed into the grid as electricity and thermal demand which includes heating and domestic water service (thermal energy is assumed unsalable here). The building also has to be low in energy consumption in the first place but still offering a comparatively good indoor thermal and air quality environment. In this study, the EnergyPlus building model is based on International Energy Conservation Code (IECC) 2012 standard, which offers low energy demand given its high thermal quality and building system design [23]. The type of energy balance here refers to primary energy balance instead of site energy balance considering primary energy use is more comparable among different buildings using different energy types (mainly electricity and gas) for their demand.

2. Developing future local hourly weather data

2.1. Climate model selection

In this paper, the Global Climate Model (GCM) — HadCM3, developed at the Hadley Center in the United Kingdom, is adopted to generate future weather data files. HadCM3, like other GCMs, is a grid point geographic model with large grid cells (2.5° latitude and 3.75° longitude over land areas, which gives 96 × 73 grid points on the scalar grid) [24]. It is high in resolution compared with some GCMs and more importantly, it has high temperature sensitivity, which is vitally important for computing building energy performance. The outputs of the model are monthly means for each climatic variable in the chosen future period. This model has been used in some building energy related research [25,26]. In this research, the most recent run of the HadCM3 model's outputs is used (IPCC Fourth Assessment Report (AR4)).

With each GCM, a set of carbon emission scenarios of the "Special Report: Emission Scenarios" (SRES) are assigned according to IPCC, namely A1FI, A2, B1, etc. [27]. These scenarios are described in the IPCC's Third Assessment Report (TAR) and Fourth Assessment Report (AR4). In this paper, the A2 scenario and the B1 scenario are selected to predict future weather data, and the projection period of 2040–2069 is chosen because we assume that the building was built in the year 2012 and the selection of the projection period (2040–2069) depends on the premise that a NZEB has a life of fifty years from 2010 as described in the former section. The A2 scenario is characterized by a heterogeneous world with independently operating, self-reliant nations; continuously increasing population; regionally oriented economic development; and slower and more fragmented technological changes, while B1 represents a world more integrated, and more ecologically friendly, but with rapid economic growth. It is a storyline with rapid changes towards a service and information economy [28].

2.2. Downscaling of the Global Climate Model

GCM runs on a coarse grid model based on the numerical solution methodology of Navier-Stokes equations to reduce the needed computational resources and expense. Merely studying the broad change obtained from the result of the Global Climate Model (GCM) is insufficient to evaluate precisely the impact of GCC on a building, and higher accuracy and resolution would anyway require detailed building energy performance profile that must be obtained by running simulation tools, like EnergyPlus, DOE 2 or TRNSYS, based on hourly weather data information. Moreover, for RE systems relying strongly on natural resources, which are thus strongly impacted by climate conditions, like PV (for solar radiation) or wind (wind speed), influences on the energy efficiency of these systems are expected to take place under the future climate condition change [7,29–32]. The method of obtaining future local hourly climate data (downscaling) based on simplified analysis of adding monthly mean change in climate variables to existing weather data file would be inaccurate and insufficient to quantify and compare the GCC impacts on NZEB performance.

Since the limited-area modeling is quite expensive in computational effort, a methodology presented by Belcher et al., which adjusts present day design weather data by the changes to climate forecast by GCM and regional climate models based on a time series methodology, is adopted here to downscale the future hourly weather data [33]. By applying this morphing downscaling method to the outcome of HadCM3, we are able to predict future hourly weather data from GCM, which gives changes to monthly mean value of weather variables.

2.2.1. Representative cities for the US climate zones

The major climate zones in United States are Cold and very cold climate zone, Hot-dry and mixed dry climate zone, Hot and humid climate zone, Marine climate zone, and Mixed-humid climate zone [34]. To find the implication of GCC on future building energy performance and NZEB, certain specific places should be chosen to locate the grid cell in which the morphing method is carried out and further building performance simulation is implemented. Fig. 1 shows the climate zone division according to the IECC [23], and we have chosen 10 cities in the US which are representatives for their respective climate zones, as shown in Table 1.

2.2.2. Typical meteorological year

In the morphing method, certain "baseline climate" is entailed, which is defined as the present-day weather sequence averaged over a number of years. The World Meteorological Organization recommends using an averaging period of 30 years to define a climate baseline, and using the period 1961–/1990 to define the 'normal' baseline for climate reference [35]. The averaging period for the baseline climate should be the same period as the baseline used for the GCC scenarios. Thanks to the US National Solar Radiation Data Base archives, the typical meteorological year data for the US can be found in the TMY3 dataset, which contains 1020 locations in the United States and its territories [36].

2.2.3. Morphing method

This research uses the morphing method proposed by Belcher et al., with detailed information about the method available in Ref. [33]. The first step of this method is to calculate the mean value for each climate variable of each month m for the baseline scenario (here refers to TMY3), the baseline climate value of x_0 for month m is defined to be:

$$\langle x_0 \rangle_m = \frac{1}{24 \times d_m} \sum_{\text{month } m} x_0 \tag{1}$$

where d_m is the number of days in a month m and the 24 comes from averaging the hourly measurements over the 24 h of each day.

The morphing method adopted here includes three operations, which can be described as: 1) a shift; 2) a linear stretch (scaling factor); 3) a shift and a stretch, the following equations demonstrates the three operations

$$x = x_0 + \Delta x_m \tag{2}$$

$$x = \alpha_m x_0 \tag{3}$$

$$x = x_0 + \Delta x_m + \alpha_m \times (x_0 - \langle x_0 \rangle_m) \tag{4}$$

where x_o is the existing hourly climate variable, Δx_m is the absolute change in monthly mean climate variable for month m (which is obtained from GCM outcome), α_m is the fractional change in monthly mean climate variable for month m, and $\langle x_0 \rangle_m$ is the climate variable x_o average over month m.

The adding of absolute change in monthly mean climate variables for a certain month is called "shift". It indicates that the mean value in a baseline scenario experiences an absolute change, like the change in atmospheric pressure. A "stretch" is used when the change of certain variable is embodied as fractional change rather than absolute increment, like solar radiation which can be zero at night. The combination of stretch and shift can be applied to variables like dry-bulb temperature, where both fractional diurnal change and absolute increment take place, especially when taking into account the changes in both maximum and minimum daily

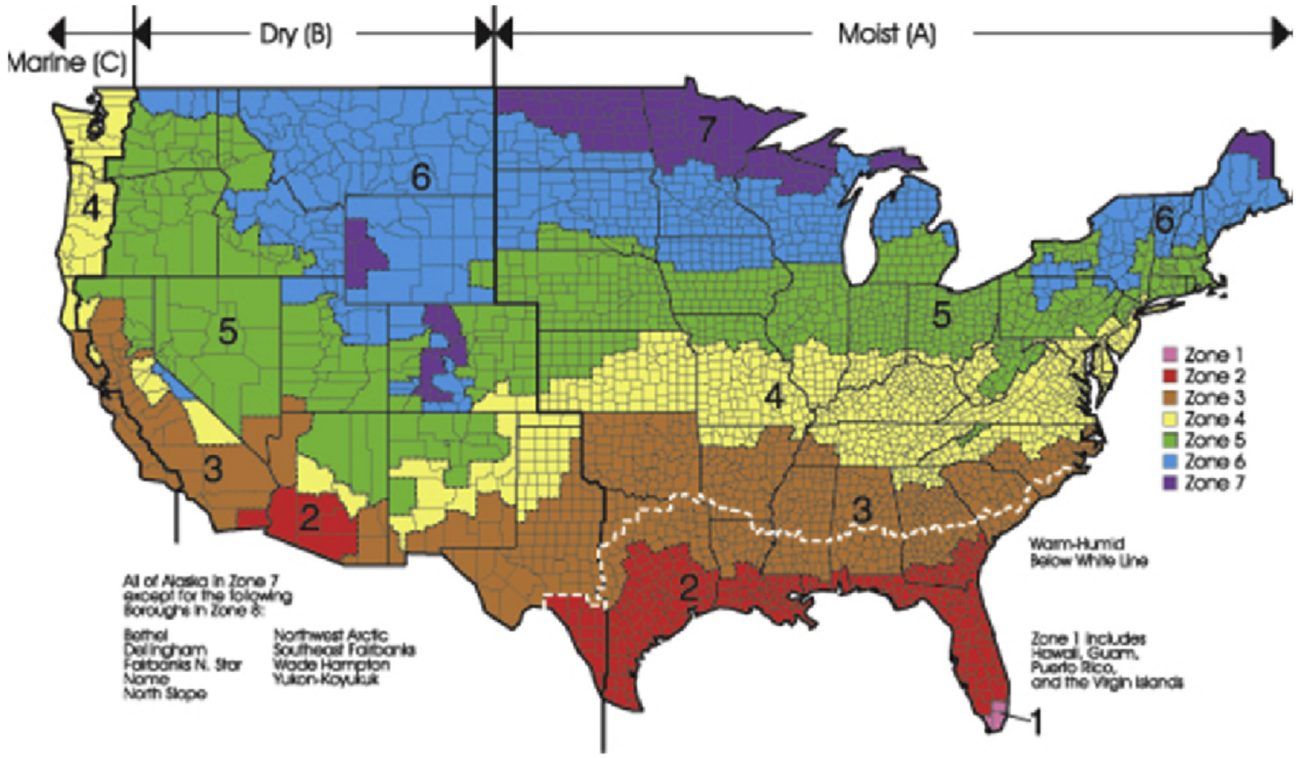


Fig. 1. United States climate zones (source: IECC).

Table 1
Ten chosen cities and their climate zones.

Climate zone	Thermal criteria	City	Latitude	Longitude
1A	5000 < CDD 10 °C	Miami_FL	25.82 N	80.3 W
2A	3500 < CDD 10 °C ≤ 5000	Houston_TX	30 N	95.37 W
2B	3500 < CDD 10 °C ≤ 5000	Phoenix_AZ	33.45 N	111.98 W
3A	2500 < CDD °C ≤ 3500 & HDD 18 °C ≤ 3000	Memphis_TN	35.07 N	89.98 W
3C	HDD 18 °C ≤ 2000	San Francisco_CA	37.62 N	122.4 W
4A	CDD 10 °C ≤ 2500 & HDD 18 °C ≤ 3000	Philadelphia_PA	39.87 N	75.23 W
4B	CDD 10 °C ≤ 2500 & HDD 18 °C ≤ 3000	Albuquerque_NM	35.04 N	106.62 W
5A	3000 < HDD 18 °C ≤ 4000	Chicago_IL	41.98 N	87.92 W
6A	4000 < HDD 18 °C ≤ 5000	Burlington_VT	44.47 N	73.15 W
7	5000 < HDD 18 °C ≤ 7000	Duluth_MN	46.83 N	92.22 W

Note: CDD: cooling degree day; HDD: heating degree day.

temperatures. After applying the stretch and/or shift changes to specific climate variables, the future hourly weather data can be morphed on the basis of current TMY hourly weather data.

2.3. Downscaling results

Table 2 shows the averages of the annual values of climate variables (temperature, relative humidity (RH), horizontal solar irradiance (hor_solar), and wind speed) for the ten cities from the year of 2040–2069. The reason why 'global climate change' is more suitable than the wording 'global warming' is shown in the table, indicating that though the temperature will be on the rise in most of the cities, in some places like Phoenix, Albuquerque, and Philadelphia, the annual mean temperature will experience a slight drop. In Fig. 2, the monthly mean temperature under TMY, B1, and A2 for Albuquerque, Phoenix, San Francisco, and Duluth, are shown, respectively. It can be observed that the trend and magnitude of global temperature rise are unequivocal – in place like Albuquerque, the temperature pattern change is very slight but it indicates a wider range of temperature distribution in the future; in Phoenix, the global climate change is pulling down the surface temperature in that region; In San Francisco and Duluth, the temperature rise is obvious and may cause greater cooling energy use and less heating energy use for the buildings in existing climate conditions; while in Duluth, the future climate may be subject to more extreme weather conditions like higher summer mean temperature and more severe coldness in during winter.

3. Building modeling and simulation

In this study, a prototypical residential buildings with different thermal properties and building system design in the ten climate zones is used to study the GCC impacts on achieving NZEB in the US. The prototypical building is equipped with electric household appliances, mechanical system and boiler. The primary energy source of the house is composed of electricity and natural gas. Then, RE systems is configured to meet the energy demand of the building. It is important to first understand the energy use pattern of the building in different climate zones. To understand the GCC impacts on the energy demand of the residential building, building

Table 2
Averages of annual mean values of climate variables in the ten cities from 2040 to 2069.

City	TMY_Temperature (°C)	B1_Temperature (°C)	A2_Temperature (°C)
Miami	24.51	27.59	27.77
Houston	20.36	22.22	22.31
Phoenix	23.80	21.13	21.15
Memphis	17.04	18.33	18.65
San Francisco	13.79	15.31	15.60
Philadelphia	12.75	11.43	11.90
Albuquerque	13.68	13.23	13.46
Chicago	9.99	9.38	9.92
Burlington	7.87	8.27	8.73
Duluth	4.02	5.08	5.63
	TMY_RH(%)	B1_RH(%)	A2_RH(%)
Miami	72.61	75.52	75.54
Houston	73.00	68.21	68.44
Phoenix	34.23	39.05	39.30
Memphis	65.61	68.17	67.18
San Francisco	74.48	82.41	82.28
Philadelphia	65.98	70.39	70.31
Albuquerque	42.40	53.39	53.00
Chicago	70.34	80.24	79.54
Burlington	67.83	80.38	80.44
Duluth	71.56	82.64	82.36
	TMY_wind(m/s)	B1_wind(m/s)	A2_wind(m/s)
Miami	4.12	4.24	4.21
Houston	3.44	3.46	3.57
Phoenix	2.76	2.68	2.67
Memphis	3.65	3.62	3.59
San Francisco	4.67	4.66	4.70
Philadelphia	4.18	4.09	4.10
Albuquerque	3.90	3.88	3.91
Chicago	4.56	4.77	4.81
Burlington	4.21	4.23	4.25
Duluth	4.63	4.69	4.59
	TMY_hor_solar(W/m^2)	B1_hor_solar(W/m^2)	A2_hor_solar(W/m^2)
Miami	200.13	232.14	232.67
Houston	185.78	211.99	211.15
Phoenix	239.06	243.58	243.20
Memphis	187.20	197.37	196.81
San Francisco	195.94	190.11	190.62
Philadelphia	167.70	182.38	181.15
Albuquerque	226.07	223.93	223.10
Chicago	160.58	169.39	166.63
Burlington	153.11	158.24	155.13
Duluth	153.23	149.88	146.82

simulation is conducted by using the downscaled local hourly weather data. We take means for each hour's climatic variables in a year downscaled from GCM outputs during years 2040–2069 to obtain representative energy use profile during the period and avoid extreme weather conditions in a specific year. This will not lose the extremity in the future climate conditions if extreme weather conditions constantly happen during that period of time. The future hourly weather data is compiled and formatted in a.epw file (the weather file format that EnergyPlus is able to read), which is used as weather data input for EnergyPlus 8.2 [37].

3.1. Building description

To make the building low in energy use intensity (EUI) so as to make it as zero-energy as possible, the prototypical buildings in different climate zones are designed with different building envelopes (wall, fenestration, roof) and HVAC system capacities according to the IECC latest most strict 2012 IECC building code while they share the same occupancy behavior, house equipment, and system schedule. The building is a two storey residential building with a total floor area of 446 m^2. The properties of the building envelopes and HVAC systems are shown in Table 3 and Table 4.

3.2. Building simulation results

Running a building simulation by EnergyPlus produces the hourly values of electricity and thermal demand under different scenarios in the four cities from the year of 2040–2069. Table 5 shows the end-use demand breakdown of the buildings under TMY condition, and Table 6 shows the annual future energy demand of the 10 cities under different SRES compared with the current TMY condition.

The energy demand results shown in Table 5 demonstrate that the buildings are consuming low amounts of energy per unit floor area. Those buildings in climate zones with extreme cold winter (Burlington and Duluth) which rely greatly on gas are using 83.7 kWh/m^2/year and 89.2 kWh/m^2/year energy, respectively, indicating good potential for achieving NZEB. Table 6 shows that the annual future electricity demand in the building will generally rise. However, the general thought that the future building thermal demand will fall turns out to be wrong since the thermal demands for Phoenix, Philadelphia, Albuquerque, and Chicago under the B1 scenario are actually rising, which is a warning sign informing about the potential of the occurrence of more extreme weather conditions in summer and winter for these regions, which might

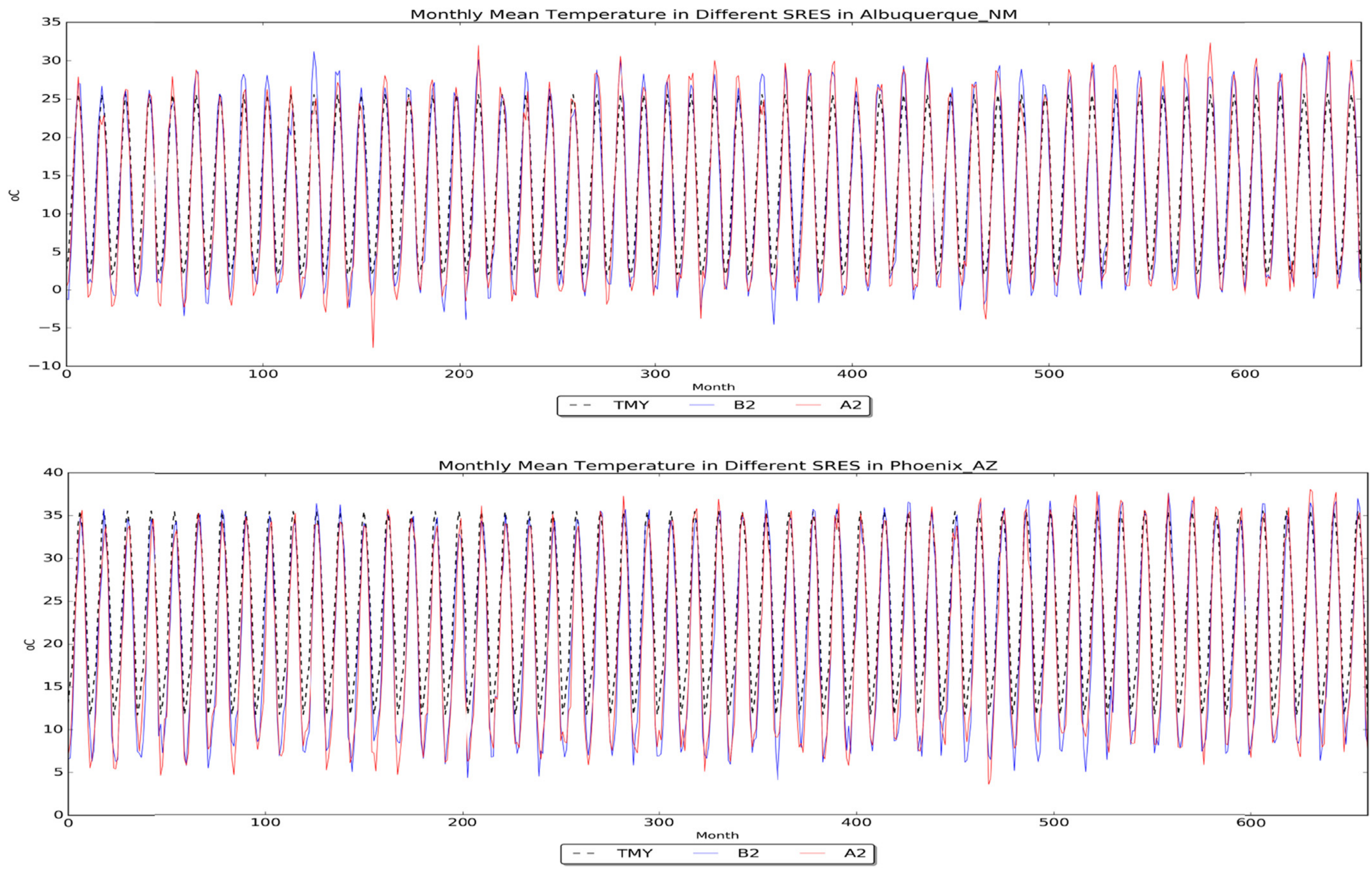


Fig. 2. Downscaled monthly mean temperature under different SRES (2015–2069) in Albuquerque, Phoenix, San Francisco, and Duluth.

incur both higher peak demand of electricity and heat as compared with that under TMY weather condition.

4. Renewable energy system modeling and simulation

According to the IPCC special report, RE systems will be remarkably influenced by extreme climate events [38]. Wind power, solar power and other types of onsite RE generation are closely related to a stable requirement for the climatic wind speed, sunshine, temperature, etc. [7,29–32]. Since the designing and sizing of onsite RE system of an NZEB is inseparable from the climatic elements and building energy demand, it would be imprecise to evaluate the RE system's performance by a comparatively coarser method of using monthly or annual energy demand and sizing estimation, especially under the circumstances that the wind and solar resources on which these system performance greatly rely are subject to change in the future climate during 2040–2069. In this research, we build the hourly RE system modeling procedure for coupling the electricity and thermal demands of the buildings and the power generation from the RE system. The modeling and simulation procedure of the RE system is discussed, and the modeling of the RE system's environmental resources is analyzed in detail below.

4.1. Renewable energy system modeling

The RE system model in this study is mainly composed of the energy load (both electric and heat), grid, inverter, photovoltaic system, wind power generation system, and solar heating collectors. The PV panels generate DC output current and the inverter of the PV system converts DC to AC to meet the electric load of the residential building. The wind turbine generates AC power for the building. The solar heating system is based on flat plate collectors to supply a part of the thermal load of the house, and is used as an auxiliary heating method. The rest of the heating load is covered by gas heating. A heat storage system is not used and the energy collected by the solar thermal system is delivered by water straight through the heat exchanger to meet the instantaneous heating load, and any extra heat collected by the solar thermal system is not captured and stored.

4.1.1. Building-integrated photovoltaic system

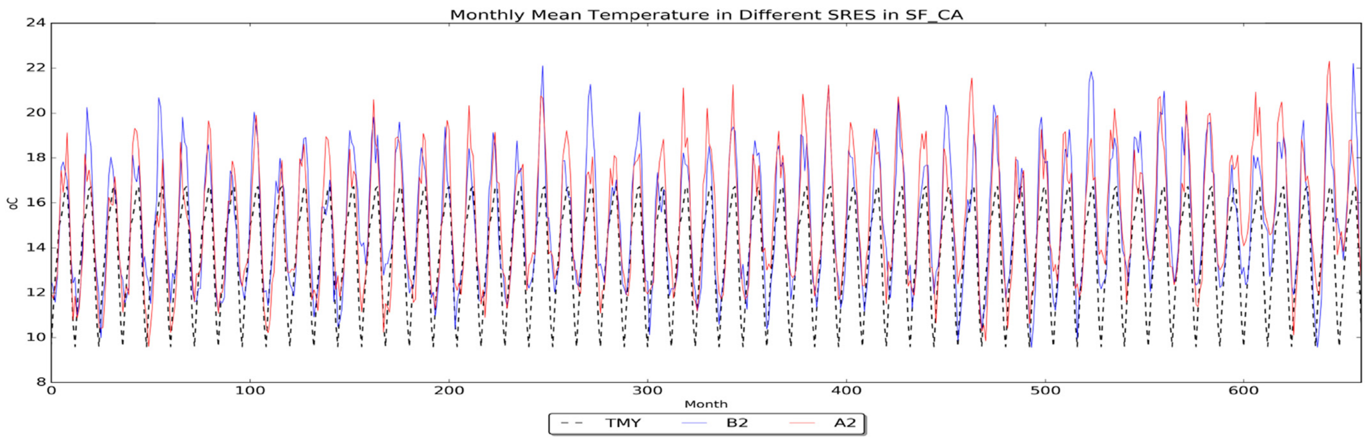
The power output of the PV system is calculated by a method proposed by Erbs et al. [39]:

$$P_{pv} = n_{pv}\mu_{pv}S_{pv}\, I_{pv}(1 - 0.005(t_a - 25))[kW] \quad (5)$$

where n_{pv} is the number of panels, S_{pv} is the array area (2 m^2), and μ_{pv} is the conversion efficiency of the solar cell used for the array. The solar cell used here is poly-crystalline silicon (p-Si) which has an efficiency of 14% [40]. I_{pv} is the solar radiation incident on the panel surface (kW/m^2), and t_a is the outside air temperature. Effects of the irradiation incidence angle are not considered in this study.

4.1.2. Wind power generation system

Wind is also one of the most important onsite RE sources, in which wind turbines makes use of wind energy to generate electricity by driving an electric generator. The equation describing the output power of the wind turbine is [41]:



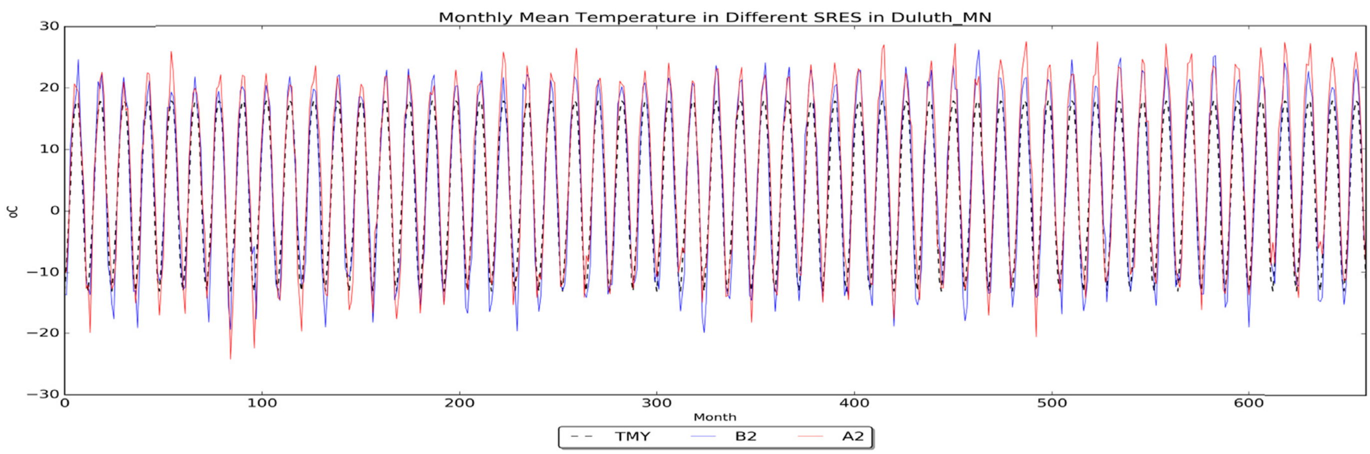


Fig. 2. (*continued*).

$$P_m = \frac{1}{2}C_p(\lambda, \beta)\rho A v_{wind}^3 \ [kW] \quad (6)$$

where,

P_m = mechanical output power of the turbine (kW); C_P = performance coefficient of the wind turbine which includes the efficiency of the electric generator, dimensionless; λ = tip speed ratio of the rotor blade tip speed to wind speed, dimensionless; β = blade pitch angle, in degree; ρ = air density (kg/m^3); A = turbine swept area (m^2); V_{wind} = wind speed (m/sec). The converter efficiency is assumed to be 0.85.

The turbine type selected for this project is SW Skystream 3.7, which has a rated power of 1.8 kW AC. The power curve of the turbine is shown in Fig. 3. Detailed description of this model can be found in Ref. [42].

4.1.3. *Solar thermal collector*

The solar thermal energy collected by the system can be calculated by:

$$Q_{sh} = \mu_{sh} S_{sh} I_{sh} \mu_{ex} \ [kW] \quad (7)$$

where μ_{sh} is the heat collection efficiency, which is 60% [44] (this value is an averaged performance value of the 10 cities, and it could

Table 3
Thermal properties of the building construction material.

	Wall construction		Roof construction		Fenestration construction			Shading
	Reflectance	U-factor [W/m^2-K]	Reflectance	U-factor [W/m^2-K]	U-factor [W/m^2-K]	SHGC	Visible transmittance	Window control
Miami	0.3	0.495	0.3	1.809	2.843	0.252	0.882	Interior Blind
Houston	0.3	0.495	0.3	1.809	2.273	0.252	0.882	Interior Blind
Phoenix	0.3	0.495	0.3	1.809	2.273	0.252	0.882	Interior Blind
Memphis	0.3	0.348	0.3	1.809	1.988	0.252	0.882	Interior Blind
San Francisco	0.3	0.348	0.3	1.809	1.988	0.252	0.882	Interior Blind
Philadelphia	0.3	0.348	0.3	1.809	1.988	0.394	0.882	Interior Blind
Albuquerque	0.3	0.348	0.3	1.809	1.988	0.394	0.882	Interior Blind
Chicago	0.3	0.348	0.3	1.809	1.818	0.394	0.882	Interior Blind
Burlington	0.3	0.300	0.3	1.809	1.818	0.394	0.882	Interior Blind
Duluth	0.3	0.300	0.3	1.809	1.818	0.394	0.882	Interior Blind

Note: U-factor: overall heat transfer coefficient, W/m^{2}K ; SHGC: solar heat gain coefficient.

Table 4
Configurations of HVAC systems for the building in ten climate zones.

	DX cooling coils: Electricity			DX heating coils: Gas	
	Total capacity [W]	Sensible heat ratio	Efficiency [W/W]	Total capacity [W]	Efficiency [W/W]
Miami	7268.30	0.74	3.97	3439.23	0.78
Houston	7539.04	0.76	3.97	6144.18	0.78
Phoenix	9112.46	0.80	3.97	4404.01	0.78
Memphis	6719.99	0.76	3.97	6467.76	0.78
San Francisco	4186.30	0.80	3.97	3412.87	0.78
Philadelphia	6820.20	0.77	3.97	7225.52	0.78
Albuquerque	7437.74	0.80	3.97	5735.02	0.78
Chicago	6940.14	0.77	3.97	9158.71	0.78
Burlington	5475.56	0.80	3.97	9408.90	0.78
Duluth	5056.89	0.80	3.97	9757.33	0.78

Note: DX: direct expansion.

Table 5
Demand breakdown per total floor area of the buildings in ten cities under TMY condition [kWh/m^2/y].

City	Cooling	Heating	Lighting	Others	Domestic hot water	Total use
Miami	14.52	10.45	3.24	15.03	2.24	45.48
Houston	10.94	23.26	3.24	15.03	2.24	54.71
Phoenix	16.49	16.59	3.24	15.03	2.24	53.59
Memphis	8.66	29.21	3.24	15.03	2.24	58.38
San Francisco	2.10	24.88	3.24	15.03	2.24	47.49
Philadelphia	6.52	41.67	3.24	15.03	2.24	68.70
Albuquerque	7.30	30.10	3.24	15.03	2.24	57.91
Chicago	6.02	53.82	3.24	15.03	2.24	80.35
Burlington	4.31	58.93	3.24	15.03	2.24	83.74
Duluth	2.81	66.09	3.24	15.03	2.24	89.42

Table 6
Annual energy use of the buildings under different SRES (kWh/year).

City	TMY_electricity	B1_electricity	A2_electricity	TMY_thermal	B1_thermal	A2_thermal
Miami	32.8	39.1 (6.3)	39.7 (6.9)	12.7	10.8 (−1.8)	10.8 (−1.8)
Houston	29.2	33.2 (3.9)	33.3 (4.1)	25.5	23.2 (−2.3)	23.1 (−2.4)
Phoenix	34.8	34.5 (−0.2)	34.4 (−0.4)	18.8	26.7 (7.9)	26.4 (7.5)
Memphis	26.9	29.7 (2.7)	30.0 (3.1)	31.4	31.6 (0.2)	31.2 (−0.2)
San Francisco	20.4	20.2 (−0.2)	20.3 (−0.1)	27.1	21.6 (−5.5)	21.0 (−6.2)
Philadelphia	24.8	25.4 (0.6)	25.7 (0.9)	43.9	50.1 (6.2)	49.1 (5.2)
Albuquerque	25.6	27.0 (1.4)	27.1 (1.5)	32.3	36.7 (4.3)	36.4 (4.0)
Chicago	24.3	24.6 (0.3)	25.1 (0.8)	56.1	58.2 (2.1)	57.5 (1.5)
Burlington	22.6	22.6 (0)	22.8 (0.2)	61.2	57.9 (−3.3)	57.0 (−4.2)
Duluth	19.2	20.5 (1.3)	20.7 (1.5)	70.1	65.0 (−5.1)	63.5 (−6.6)

be different due to geographic locations); S_{sh} is the total heat collection area (2 m^2 per panel), and I_{sh} is the solar irradiation incident on the thermal collector system surface (kW/m^2), μ_{ex} is the efficiency of the heat exchanger set as 55%.

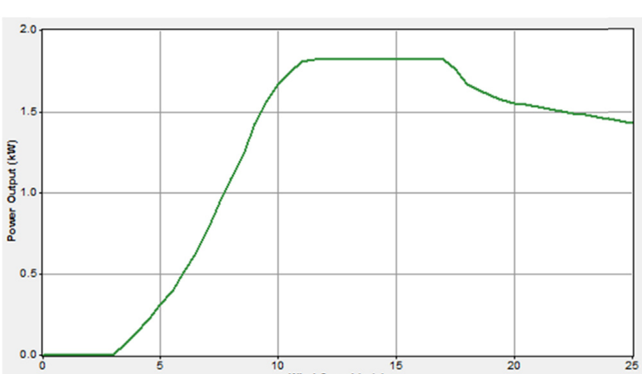


Fig. 3. Power curve of the selected wind turbine [43].

4.2. Onsite renewable energy system load and resource

4.2.1. The solar resource

The electricity generated by the PV system and the heat produced by the solar thermal collector system are directly impacted by the solar irradiation. The hourly data of solar irradiation in B1 and A2 scenarios downscaled from TMY baseline scenarios are read directly from the epw weather file, and it should also be noted that the 30 year's hourly data has been averaged to get the "average" weather condition during 2040–2049, and it also applies to other weather variables. The annual means of the solar resources can be found in Table 2.

4.2.2. The wind resource

The input of the wind resource generates the electricity by a wind turbine. The wind resource parameters in the ten cities are calculated based on the TMY baseline wind data. The morphed future hourly wind data are used to calculate the hourly generated electricity by the wind turbines. Table 7 shows the parameters of the wind resource profile. The Weilbull k value is a parameter that indicates the breadth of the distribution of wind speeds. Lower k

Table 7
Wind resource parameters in ten cities.

City	SRES	Weibull k	Autocorrelation factor	Diurnal pattern strength	Hour of peak wind speed	Scaled annual average
Miami	TMY	2.02	0.787	0.299	15	4.12
	B1	1.99	0.779	0.306	15	4.24
	A2	2.04	0.754	0.31	15	4.21
Houston	TMY	2.03	0.737	0.374	15	3.44
	B1	1.81	0.724	0.431	15	3.46
	A2	1.82	0.72	0.433	15	3.57
Phoenix	TMY	1.8	0.646	0.216	14	2.76
	B1	1.89	0.603	0.222	14	2.68
	A2	1.9	0.605	0.221	14	2.67
Memphis	TMY	1.94	0.804	0.231	13	3.65
	B1	2.07	0.769	0.248	13	3.62
	A2	2.06	0.768	0.249	13	3.59
San Francisco	TMY	1.64	0.828	0.376	17	4.67
	B1	1.58	0.839	0.375	17	4.66
	A2	1.6	0.837	0.376	17	4.70
Philadelphia	TMY	2.13	0.817	0.196	14	4.18
	B1	2.04	0.824	0.198	14	4.09
	A2	2.03	0.827	0.198	14	4.10
Albuquerque	TMY	1.65	0.726	0.232	17	3.9
	B1	1.65	0.716	0.221	17	3.88
	A2	1.65	0.718	0.221	17	3.91
Chicago	TMY	2.21	0.819	0.209	14	4.56
	B1	2.29	0.789	0.217	14	4.77
	A2	2.28	0.79	0.216	14	4.81
Burlington	TMY	1.94	0.823	0.198	13	4.21
	B1	1.98	0.813	0.203	13	4.23
	A2	1.98	0.813	0.203	13	4.25
Duluth	TMY	2.27	0.856	0.179	14	4.63
	B1	2.31	0.844	0.185	14	4.69
	A2	2.31	0.842	0.187	14	4.59

values means broader distributions of wind speed while higher k values means narrower wind speed distributions. The autocorrelation factor is used to indicate how strongly the wind speed in 1 h depends on the previous hours. Low values of the autocorrelation factor, like in Phoenix or Houston, indicate that these cities are surrounded by complex topography such as having mountains on one side and open water or plains on the other, because shifts in wind direction in these places can cause the wind to have a very variable character and low persistence of wind speeds. The diurnal pattern strength is a measure of how strongly the wind speed tends to depend on the time of day. Higher diurnal value implies that the wind speeds are more dependent on solar radiation.

4.3. Micro power system modeling

A micropower system is a system that generates electricity, and possibly heat, to serve a nearby load, which may be grid-connected or autonomous. Here, it refers to the onsite renewable energy systems including PV, wind, and solar panels. The electricity load of the building will be met by the energy produced by the PV panel and wind power generation system, which can be explained by functions of weather variables including solar irradiation, air temperature, and wind speed; the thermal energy provided by unit solar thermal panel is expressed as a function of irradiation.

$$P_{pv} = E_{inv}\sum_{1}^{p} f(I_i , T_i)\ [kW] \tag{8}$$

$$P_{tb} = \sum_{1}^{t} h(W_i)\ [kW] \tag{9}$$

$$Q_{sh} = \sum_{1}^{s} g(I_i)\ [kW] \tag{10}$$

where I_i,T_i,W_i are solar irradiation (kW/m^2), air temperature (°C), and wind speed at each hour (m/s); p, t, s are the numbers of PV panels, wind power generation system, and number of solar heating panels, respectively. P_{pv},P_{tb},P_{sh} are hourly power output of the PV, wind, and solar heating system, respectively.

Then the net electricity and net heat production per time step will thus be:

$$n_{elec} = \left(P_{pv} - \frac{d_{elec,i}}{E_{inv}}\right) e_{inv} + P_{tb} = e_{inv}\sum_{1}^{p} f(I_i , T_i) - d_{elec,i} + \sum_{1}^{t} h(W_i)\ [kW] \tag{11}$$

$$n_{therm} = \begin{cases} Q_{sh} - d_{therm,i} = \sum_{1}^{s} g(I_i) - d_{therm,i} , & Q_{sh} \le d_{therm,i} \\ 0, & Q_{sh} > D_{therm,i} \end{cases}\ [kW] \tag{12}$$

where $d_{elec,i}$ and $d_{therm,i}$ is electricity and thermal demand per hour (kW); e_{inv} is the inverter efficiency which is assumed to be 0.92. Net electricity and Net thermal value being positive means that the energy production from the RE system is having surplus while them being negative means that the energy production from RE is in deficit. n_{elec},$n_{thermal}$ are hourly net electricity and net thermal energy in kW, respectively.

The annual total production of the PV, wind power generation system, and solar heating systems, for net electricity and net heat is thus:

$$E_{pv} = e_{inv}\sum_{i=1}^{8760} \sum_{1}^{p} f(I_i , T_i)\ [kWh] \tag{13}$$

$$E_{tb} = \sum_{i=1}^{8760} \sum_{1}^{t} h(W_i)\ [kWh] \quad (14)$$

$$E_{sh} = \begin{cases} \sum_{i=1}^{8760} d_{therm,i}, & (for\ all\ Q_{sh} \le d_{therm,i}) \\ \sum_{i=1}^{8760} \sum_{1}^{s} g(I_i), & (for\ all\ Q_{sh} > D_{therm,i}) \end{cases} [kW] \quad (15)$$

$$N_{elec} = e_{inv} \sum_{i=1}^{8760} \sum_{1}^{p} f(I_i, T_i) - \sum_{i=1}^{8760} d_{elec,i} + \sum_{i=1}^{8760} \sum_{1}^{t} h(W_i)\ [kWh] \quad (16)$$

$$N_{therm} = \sum_{i=1}^{8760} \sum_{1}^{s} g(I_i) - \sum_{i=1}^{8760} d_{therm,i}\ (for\ all\ Q_{sh} \le d_{therm,i})\ [kWh] \quad (17)$$

where E_{pv}, E_{tb}, E_{sh} are the total annual production of the PV system, wind system, and solar heating system in kWh, respectively. N_{elec} and N_{therm} are annual net electricity and net thermal energy in kWh, respectively.

4.4. Net zero energy building criterion

Most analyses use the energy measured at the site, which is useful for understanding the performance of the building and the building systems, but it is not a good indicator for the environmental impacts from resource consumption and emissions associated with energy use. Site energy is also not a good metric for comparing buildings that use different energy types, with on-site energy generation such as photovoltaic system, or buildings with cogeneration systems. It is scientifically improper to assume that the same amount of electricity and natural gas (in kWh) being consumed by a building has the same environmental impact when considering the different processes of exploiting, generating, transmission, and distribution losses associated with these two different types of energy. For example, the amount of electricity supplied to the building is typically generated by investing more than twice the amount of the natural gas having the same number of energy units due to electric power plant efficiency and distribution losses. The primary energy factor should thus be determined and used to determine how much electricity consumed by the building is equal to 1 unit of natural gas being consumed by the boiler. According to the source energy factor provided in EnergyPlus 8.2, the primary energy factor for natural gas is 1.084, and is 3.167 for electricity [37]. Thus, we define whether the building is a NZEB by the following rules:

$$if\ NetZero(sys) = \begin{cases} True, & 3.167\ N_{elec} + 1.084\ N_{therm} \ge 0 \\ False, & 3.167\ N_{elec} + 1.084\ N_{therm} < 0 \end{cases} \quad (18)$$

4.5. Grid search for system configuration space

We designed a simple grid-searching method for achieving NZEB with the minimal system cost – here, since we are not doing economic analysis in the research, the cost is replaced here by the number of units needed for each RE system as we may consider that as the resource that should be minimized. *pv*, *tb*, *sh* are the number of PV panels, number of wind power generation system, and the number of solar heating panels, respectively. We define the search space of each system's resources as linear design space. Each renewable system is made up by the combination of the linear discrete space of *pv*, *tb*, *sh*. We are configuring the system using three priority rules: priority to PV system, priority to wind system, and balanced system to study the vulnerability of the systems with different priority to future climate change. The search method for each prioritized system can be expressed by eq. (19) (20) (21) if we define the search space for the system as $\{[pv_{min} \ldots pv_{max}], [tb_{min} \ldots tb_{max}], [sh_{min} \ldots sh_{max}]\}$:

System with priority to PV:

$$sys_{[pv'_{min},\ tb_{min},\ sh_{min}]} \in \left\{ sys \,\middle|\, if\ NetZero\left(sys_{\{[pv_{min} \ldots pv_{max}],\ tb_{min},\ sh_{min}\}} \right) = True \right\} \quad (19)$$

$$pv\ number\ for\ system\ with\ priority\ to\ PV:\ pv'_{min}$$

System with priority to wind:

$$sys_{[pv_{min},\ tb'_{min},\ sh_{min}]} \in \left\{ sys \,\middle|\, if\ NetZero\left(sys_{\{pv_{min},\ [tb_{min} \ldots tb_{max}],\ sh_{min}\}} \right) = True \right\} \quad (20)$$

$$tb\ number\ for\ system\ with\ priority\ to\ \text{wind system}:\ tb'_{min}$$

The rule of searching the systems with priority to PV and wind basically sets the other two RE system's resources to be the minimum in the search space (in this research, the minimum configuration for wind system is 1, and that for PV panel area is 1/4 of the roof top area, which is 30 m^2), and then look for the optimal (least) number of panels and/or wind power generation systems to meet the NZEB criteria.

For the energy-balanced system, we take half of the wind power systems number with priority to wind and search for the combination with the minimal needed number of PV panels and minimal needed number of solar heating panels as the balanced system that meets the NZEB condition:

$$sys_{[pv''_{min},\ tb'_{min}/2\ ,\ sh''_{min}]} \in \left\{ sys \mid if\ NetZero\left(sys_{\left\{[pv_{min} \ldots pv_{max}],\ \left\lfloor \frac{tb'_{min}}{2} \right\rfloor,\ [sh_{min} \ldots sh_{max}]\right\}} \right) = True \right\} \quad (21)$$

If we call the format of the linear search space as [min, max, step] and the search range for the PV panel area to be [2, 150, 30], that for wind systems to be [1, 20, 1], and that for solar thermal panel area to be [2, 150, 30], then the results shown in Table 8 are obtained after doing a grid search for the systems in ten climate zones (the step for PV panel and solar heating panel is set at 2

Table 8
RE system configurations in ten cities under TMY scenario.

City	Priority to PV			Priority to wind system			Balanced system		
	pv_area (m^2)	tb_num	sh_area (m^2)	pv_area (m^2)	tb_num	sh_area (m^2)	pv_area (m^2)	tb_num	sh_area (m^2)
Miami	60	1	30	30	4	30	60	1	30
Houston	68	1	30	30	7	30	52	3	34
Phoenix	64	1	30	30	12	30	50	5	76
Memphis	64	1	30	30	5	30	54	2	44
San Francisco	36	1	30	30	2	30	34	1	56
Philadelphia	70	1	30	30	5	30	54	2	142
Albuquerque	48	1	30	30	3	30	48	1	30
Chicago	76	1	30	30	4	30	70	1	138
Burlington	80	1	30	30	5	30	60	2	90
Duluth	74	1	30	30	4	30	68	1	90

because each panel's area is assumed to be 2 m^2):

5. Results and discussion

After running the simulation using the RE system configurations for the buildings in each climate zones in the B1 and A2 scenarios, we found the results showing the performance of the NZEBs in each zone in the future, and they are listed in Table 9, which shows the annual net electricity and net thermal energy use of ten cities' ZEBs in different SRES. In addition, we also use the above mentioned "source energy balance" metrics to measure whether a building achieves net zero energy. The values of the rows called "surplus and deficit" are the major factor judging whether a building is NZEB. They are calculated by summing the net electricity value multiplied by 3.167 and the net thermal value multiplied by 1.084. The positively larger this value is, the building is generating more source energy than it would be using. The negatively smaller it gets, the building is buying more source energy from the grid (electricity or gas).

According to Table 9, the goal of achieving NZEB in the future weather is missed for the buildings in Miami, Phoenix, Memphis, and Albuquerque. For Duluth, the goal is not fulfilled in the B1 scenario. It is not hard to find out the reasons for the differences in achieving NZEB goals in the ten climate zones — surely it is due to the different trends and magnitudes in the changes of building's energy demand and RE system resources in various places, but it is not easy to quantifiably judge how well the NZEBs in different climate zones will be performing in the future and how much energy surplus and deficit they will have without the help of detailed hourly energy use simulation.

The results show that among these cities that are missing their goals, Miami, Memphis, and Duluth all have the trend of falling net electricity and rising net thermal energy. The large amount of decreased net electricity and the small amount of increased net thermal cannot compensate each other, even before the primary energy conversion factor has been applied in the analysis. In Phoenix, the situation is complicated because the net electricity is

Table 9
Performance of present day's RE system configuration for NZEB under future climate scenarios B1, A2 (numbers in bold red means deficit in energy balance).

City	Energy balance (kWh) type	Priority to PV system			Priority to wind system			Balanced system		
		TMY	B1	A2	TMY	B1	A2	TMY	B1	A2
Miami	Net electricity	1202.5	451.4	188.6	1805.6	37.5	−353.9	1202.5	451.4	188.6
	Net thermal	−2759.0	−2016.8	−2013.4	−2759.0	−2016.8	−2013.4	−2759.0	−2016.8	−2013.4
	Surplus and deficit	817.5	**−756.7**	**−1585.2**	2727.6	**−2067.5**	**−3303.3**	817.5	**−756.7**	**−1585.2**
Houston	Net electricity	2708.8	3088.7	2938.4	3984.2	5846.1	5596.2	2437.5	3226.7	3046.7
	Net Thermal	−7200.1	−6316.7	−6276.7	−7200.1	−6316.7	−6276.7	−7108.7	−6239.8	−6199.9
	Surplus and deficit	773.9	2934.7	2502.0	4813.1	11667.4	10919.4	13.7	3455.0	2928.3
Phoenix	Net electricity	2142.0	2516.1	2552.0	1966.2	1990.1	1984.8	1647.1	1886.4	1908.0
	Net Thermal	−5130.9	−7999.2	−7894.7	−5130.9	−7999.2	−7894.7	−4811.0	−7449.2	−7353.9
	Surplus and deficit	1221.8	**−702.7**	**−475.6**	664.9	**−2368.6**	**−2272.0**	1.1	−2100.8	−1929.1
Memphis	Net electricity	3407.3	2719.1	2501.9	3236.5	2018.3	1854.3	3044.6	2210.0	2007.7
	Net Thermal	−9270.2	−9187.3	−9056.1	−9270.2	−9187.3	−9056.1	−8862.3	−8771.4	−8651.7
	Surplus and deficit	741.9	**−1347.5**	**−1893.2**	201.2	**−3567.2**	**−3944.3**	35.5	**−2509.0**	**−3020.2**
San Francisco	Net electricity	2919.8	2853.8	2819.2	5294.8	5321.8	5288.9	2461.0	2406.5	2371.2
	Net thermal	−7558.7	−5459.0	−5222.9	−7558.7	−5459.0	−5222.9	−7180.6	−5197.6	−4977.2
	Surplus and deficit	1053.5	3120.5	3266.7	8574.9	10936.8	11088.3	10.2	1987.1	2114.4
Philadelphia	Net electricity	4919.0	5977.8	5708.0	6420.3	7035.8	6854.5	4123.9	4963.3	4726.7
	Net thermal	−13860.9	−16011.8	−15651.5	−13860.9	−16011.8	−15651.5	−12039.0	−13773.4	−13464.5
	Surplus and deficit	553.3	1574.8	1111.1	5307.8	4925.6	4742.1	10.1	788.2	374.0
Albuquerque	Net electricity	3499.2	2659.6	2529.3	3530.3	2671.5	2557.4	3499.2	2659.6	2529.3
	Net thermal	−9762.7	−11292.5	−11179.8	−9762.7	−11292.5	−11179.8	−9762.7	−11292.5	−11179.8
	Surplus and deficit	499.3	**−3818.2**	**−4108.6**	597.7	**−3780.3**	**−4019.8**	499.3	**−3818.2**	**−4108.6**
Chicago	Net electricity	6444.7	7104.8	6598.0	6737.3	6710.4	6408.0	5315.6	5907.4	5424.8
	Net thermal	−18297.8	−18984.8	−18774.5	−18297.8	−18984.8	−18774.5	−15528.8	−15969.6	−15753.5
	Surplus and deficit	575.6	1921.3	544.2	1502.2	672.1	57.4	1.4	1397.7	103.7
Burlington	Net Electricity	7064.8	7601.9	7147.7	8299.8	8469.7	8179.8	6008.9	6403.6	6021.7
	Net Thermal	−20158.4	−18777.2	−18461.2	−20158.4	−18777.2	−18461.2	−17539.3	−16394.7	−16105.5
	Surplus and deficit	522.7	3720.8	2624.8	4433.8	6468.9	5893.4	17.7	2508.3	1612.4
Duluth	Net electricity	8119.8	7357.1	7739.2	9132.3	8499.5	8731.5	7013.0	6279.1	6626.3
	Net thermal	−23494.2	−22908.0	−22122.9	−23494.2	−22908.0	−22122.9	−20486.6	−19864.2	−19240.3
	Surplus and deficit	247.6	**−1532.4**	528.9	3454.4	2085.8	3671.6	2.6	**−1647.0**	129.1

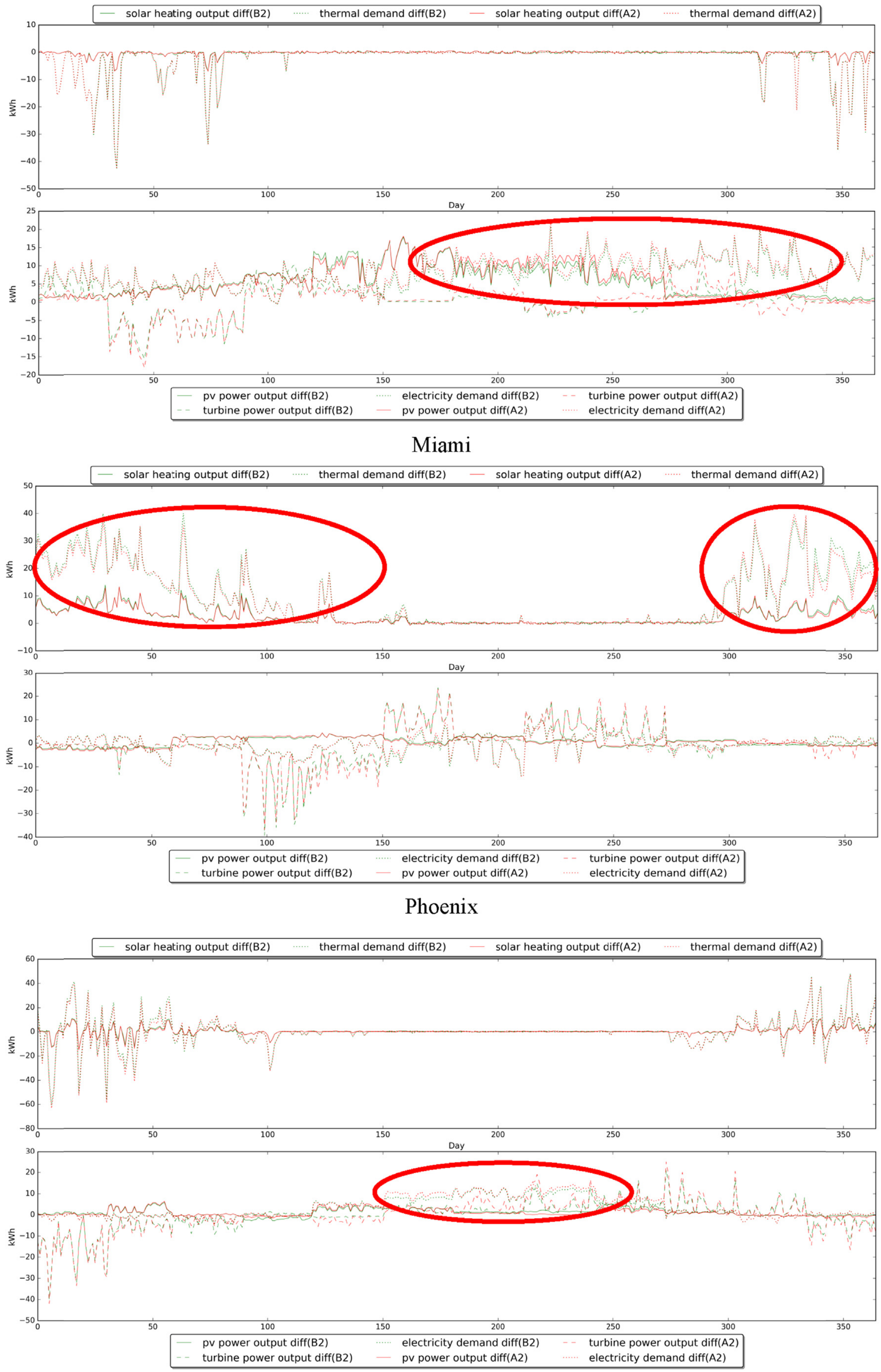


Fig. 4. Difference of daily building load and energy production of each sub system under B1 and A2 compared with TMY in Miami, Phoenix, Memphis, and Albuquerque.

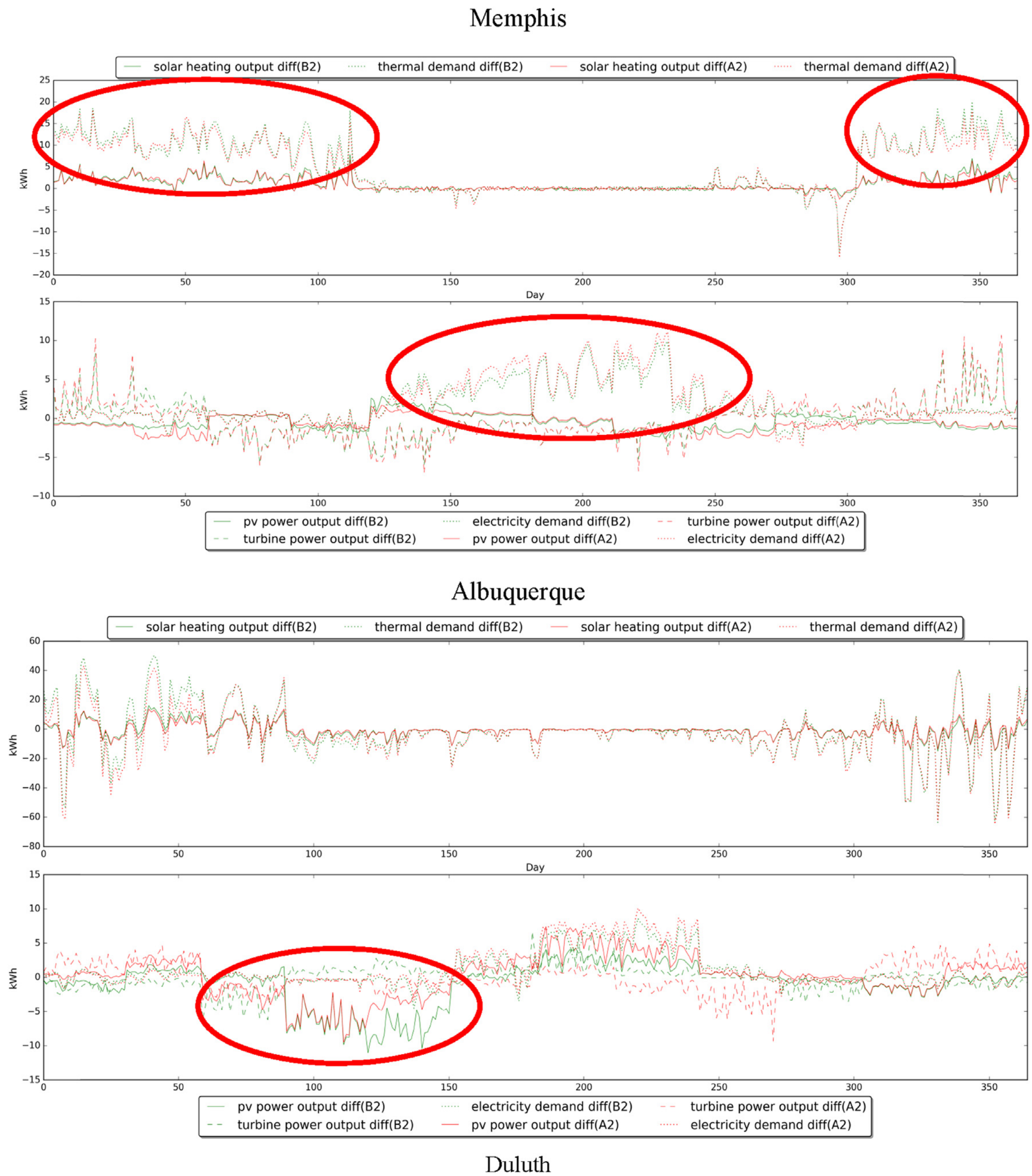


Fig. 4. (*continued*).

rising, so we may take for granted that it is not going to miss the goal. The future climate condition in Phoenix will, however, be having colder winter, which leads to a greater demand for heat. The worst case is Albuquerque where the future net electricity and net thermal are both declining, which may be due to both higher cooling and heating demand. The monthly temperature trends of Albuquerque and Phoenix can be found in Fig. 2 and the above analyses for the two cities may find its clue in their future temperature trends.

More insights are still needed for understanding in further detail what is going to happen for the performance of nowadays NZEBs in the future. The simulation results is discussed more in detail in the following sections using the RE system with a balanced configuration of PV and wind because this system is able to illustrate comprehensive effects of both PV and wind on the RE system performance.

5.1. *Climate zones missing the NZEB goal*

Fig. 4 shows a comparison of the daily energy production and building load under TMY, with that under B1 and A2 for each of the cities missing the NZEB goals. In the graphs, a positive value means more production/use and negative values mean a lower production/use when compared with the referenced TMY scenario. Since the use of lighting and other equipment in the building is fairly constant, the change in electricity and heat demand can be mostly attributed to the cooling and heating demand.

For Miami and Memphis, the present day NZEB fails to achieve NZEB in the future because it has a decreasing net electricity that cannot be counteracted by the increased net thermal energy use. In Miami, the increase in annual net heat results mainly from the decreasing thermal load as per Fig. 4. In Memphis, the annual net heat decreases very little because the rise or fall of the thermal demand in winter is rather unpredictable compared with the reference climate. For both cities, the drop in annual thermal energy demands are too small in magnitude to make up for the rise in net electricity decrease.

The electricity aspect is more complicated for the two cities but we can find that the PV system output is fairly stable and has a better performance than under the reference climate scenario, especially in Miami: its rise in daily energy output is obvious during summer and fall. For the wind system in the two places, the performance is not stable, with a worse performance in spring in Miami and at the end of the winter in Memphis. The cooling energy demand in the second half of the year in Miami and in the middle of the year in Memphis (circled part) contributes greatly to the falling net electricity.

For Phoenix, the reason why it missed the goal is because of the growing heating demand, circled in red. Though the solar heating system has a growing output in B1 and A2 scenario, it is still not able to recover the loss in greater heating demand. The minor growth in net electricity cannot make up for the growth of this part. In March and April the wind system is not performing better than referenced climate, but it recovers after May. The PV system performance is stable.

For Albuquerque, the more extreme weather conditions in the future not only raise the heating demand in winter, but also raise the cooling demand in summer. Though the wind system has a higher output during most time of the year compared with reference scenario, it is not capable to recover the rapidly growing heating and cooling demand.

Among all the cities that are missing their goals, Duluth is an exception in that the waning PV solar output is the main reason for failing to achieve NZEB. The heating and cooling load change in Duluth would nearly counteract each other in the future, which should not bring much trouble for the originally net zeroed energy building. In the B1 scenario, however, the problem of waning solar PV output is salient and finally makes it fail the NZEB target, caused by decreasing solar in that area in the future.

5.2. PV, wind, and solar thermal system

The different magnitudes of decreased or increased net electricity in Miami, Memphis, and Albuquerque where NZEB goals are missed may give us some hints about the vulnerability of RE systems to priorities we assign to PV and wind systems. The differences between PV prioritized systems under B1, A2 scenario with the reference TMY scenario are −751.1 kWh, −1013.9 kWh for Miami; 374.1 kWh, 410 kWh for Phoenix; −688.1 kWh, −905.3 kWh for Memphis; −839.7 kWh, and −969.9 kWh for Albuquerque; while the differences between wind prioritized systems under B1, A2 scenario with the reference TMY scenario are −1768.1 kWh, −1451.7 kWh for Miami; 23.9 kWh, −3950.9 kWh for Phoenix; −1218.3 kWh, −5090.8 kWh for Memphis; −858.8 kWh, and −6087.7 kWh for Albuquerque. These numbers indicate the comparatively lower stability of the RE system with priority to wind as compared with the PV-prioritized RE system. Table 10 clearly describes the subsystems' performance in the future:

$$P_{change\%} = \frac{P_{future} - P_{TMY}}{P_{TMY}} \times 100\% \quad (22)$$

$$D_{change\%} = \frac{D_{future} - D_{TMY}}{D_{TMY}} \times 100\% \quad (23)$$

where $P_{change\%}$ is the percentage change of subsystem's power output; P_{future}, P_{TMY} are the annual power output in future climate conditions, and present climate conditions, respectively $D_{change\%}$ is the percentage change of building load; D_{future}, D_{TMY} are the annual building load in the future climate condition, and present climate condition, respectively.

Among the three types of system with different priorities, we averaged the change of each subsystem's output and building load compared with the TMY scenario. Among all the NZEBs in the ten climate zone, the proportion of decreased annual PV output is 5 out of 20 (10 cities × 2 future climate scenario = 20), while that of wind is 12 out of 20, and that of solar thermal system is 10 out of 20. The main reason for most of the decreases in the solar thermal system's performance is due to the decrease in the heat load because we didn't include a heat storage system and the excess generated heat is assumed to be unsellable. We find that for most of the cities with a growing annual thermal demand, the annual solar thermal system output will rise in the future too.

The result that the PV system is more stable in power generating performance than the wind system makes sense because in most of the places the solar irradiation is expected to increase nationwide (shown in Fig. 5), while the annual average wind speed is not expected to change much for most of the climate zones. The relative instability of the wind turbine system is attributed to its power generation curve, which is shown in Fig. 3. Wind speeds of 0 m/s to 3 m/s generate almost no power and wind speeds over 17 m/s cannot be used, which requires an evenly distributed wind speed profile during a year for achieving good performance. In addition, the autocorrelation factors of the wind resource shown in Table 7 indicates that most of the sites, except San Francisco and Philadelphia, have a slight decrease, indicating a more unpredictable and unstable wind resource for the wind system. The turbine electricity output drops in most cities with decreased autocorrelation factors, but for San Francisco and Philadelphia the wind power output increases by 1.6% (B1) and 3.0%, and 1.7% (A2), 3,2%(A2), respectively.

5.3. RE system for the future

The results show that for all the cities that miss their NZEB goals in the future, the climate-driven change in heating and cooling energy demand is the main driver for that failure. Hence, NZEB with the present day's RE system configuration is very sensitive and vulnerable to the change in heating and cooling demand. Generally, the RE system configuration should be carefully designed in places with large diurnal and seasonal temperature variation (like Phoenix, Albuquerque), and with places with very low heating degree days and high cooling degree days (Miami) because the future climate is going to show more extremes in temperature, wind speed, and solar radiation there.

To make nowadays' NZEB still remain net zero in the future, we did the grid search using the same design space for PV, wind, and solar thermal collectors under different SRES, and the results are presented in Tables 11 and 12 (the numbers in parenthesis are the difference from the TMY scenario):

$$C_{change} = C_{future} - C_{TMY} \quad (24)$$

where, C_{change} is the change in subsystem's configuration;

Table 10
Average change in percentage of subsystems' power output and building load compared with the TMY scenario, according to eqs. 22 and 23

Name	City	B1 (%)	A2 (%)	City	B1 (%)	A2 (%)
PV output	Miami	15.4	15.5	Houston	12.2	11.6
Wind system output		0.2	−1.4		26.6	25.0
Solar heating output		−2.8	−2.7		−3.3	−3.6
Electricity demand		19.3	20.9		13.5	13.9
Thermal Demand		−14.5	−14.5		−9.0	−9.4
PV output	Phoenix	1.7	1.6	Memphis	4.3	3.9
Wind system output		−2.2	−2.9		−3.0	−2.8
Solar heating output		19.6	18.4		3.2	2.5
Electricity demand		−0.6	−1.1		10.2	11.5
Thermal Demand		41.8	40.1		0.5	−0.7
PV output	San Francisco	−2.5	−2.4	Philadelphia	9.3	8.3
Wind system output		1.6	1.7		3.0	3.2
Solar heating output		−8.0	−9.1		10.6	9.4
Electricity demand		−0.9	−0.4		2.5	3.8
Thermal Demand		−20.4	−22.7		14.1	11.9
PV output	Albuquerque	−1.4	−1.9	Chicago	6.0	3.9
Wind system output		−1.8	−2.0		−1.8	−1.6
Solar heating output		8.7	8.1		4.0	2.8
Electricity demand		5.4	5.9		1.4	3.3
Thermal Demand		13.4	12.4		3.8	2.6
PV output	Burlington	3.7	1.4	Duluth	−2.6	0.6
Wind system output		−0.3	−0.7		−0.9	0.3
Solar heating output		−1.1	−2.5		−2.4	−0.2
Electricity demand		0.0	1.0		4.4	5.4
Thermal Demand		−5.4	−6.9		−2.5	−4.4

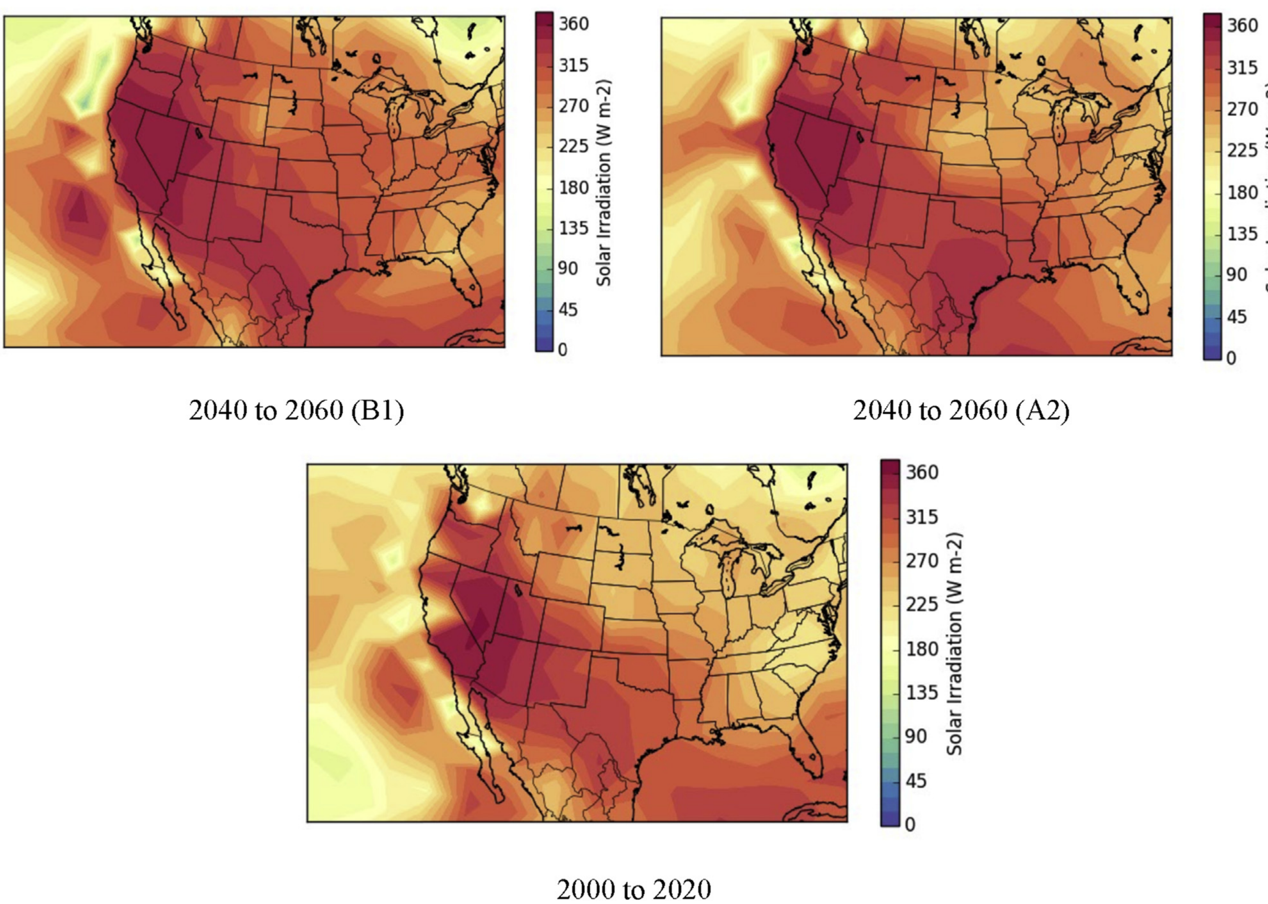


Fig. 5. Comparison of average solar irradiation in July in the period of 2000 to 2020 and 2040–2060.

C_{future}, C_{TMY} are the configuration of subsystem under future, and present climate condition respectively that enables the building to meet the NZEB target. The RE systems' vulnerability can be ranked by the numbers in the parenthesis for a system prioritized with a

Table 11
RE system configuration that meets NZEB under B1, according to eq. (24).

City	Priority to PV			Priority to wind system			Balanced system		
	pv_area (m^2)	tb_num	sh_area (m^2)	pv_area (m^2)	tb_num	sh_area (m^2)	pv_area (m^2)	tb_num	sh_area (m^2)
Miami	62 (2)	1 (0)	30 (0)	30 (0)	5 (1)	30 (0)	52 (−8)	2 (1)	30 (0)
Houston	66 (−2)	1 (0)	30 (0)	30 (0)	6 (−1)	30 (0)	56 (4)	2 (−1)	30 (−4)
Phoenix	66 (2)	1 (0)	30 (0)	30 (0)	13 (1)	30 (0)	50 (0)	6 (1)	42 (−34)
Memphis	66 (2)	1 (0)	30 (0)	30 (0)	6 (1)	30 (0)	58 (4)	2 (0)	34 (−10)
San Francisco	32 (−4)	1 (0)	30 (0)	30 (0)	2 (0)	30 (0)	32 (−2)	1 (0)	30 (−26)
Philadelphia	68 (−2)	1 (0)	30 (0)	30 (0)	5 (0)	30 (0)	54 (0)	2 (0)	74 (−68)
Albuquerque	54 (6)	1 (0)	30 (0)	30 (0)	4 (1)	30 (0)	52 (4)	1 (0)	64 (34)
Chicago	74 (−2)	1 (0)	30 (0)	30 (0)	4 (0)	30 (0)	68 (−2)	1 (0)	126 (−12)
Burlington	74 (−6)	1 (0)	30 (0)	30 (0)	5 (0)	30 (0)	56 (−4)	2 (0)	84 (−6)
Duluth	78 (4)	1 (0)	30 (0)	30 (0)	4 (0)	30 (0)	70 (2)	1 (0)	118 (28)

Table 12
RE system configuration that meets NZEB under A2,, according to eq. (24).

City	Priority to PV			Priority to wind system			Balanced system		
	pv_area (m^2)	tb_num	sh_area (m^2)	pv_area (m^2)	tb_num	sh_area (m^2)	pv_area (m^2)	tb_num	sh_area (m^2)
Miami	62 (2)	1 (0)	30 (0)	30 (0)	5 (1)	30 (0)	54 (−6)	2 (1)	30 (0)
Houston	66 (−2)	1 (0)	30 (0)	30 (0)	6 (−1)	30 (0)	56 (4)	2 (−1)	50 (16)
Phoenix	66 (2)	1 (0)	30 (0)	30 (0)	13 (1)	30 (0)	50 (0)	6 (1)	34 (−42)
Memphis	68 (4)	1 (0)	30 (0)	30 (0)	6 (1)	30 (0)	58 (4)	2 (0)	56 (12)
San Francisco	32 (−4)	1 (0)	30 (0)	30 (0)	2 (0)	30 (0)	32 (−2)	1 (0)	30 (−26)
Philadelphia	70 (0)	1 (0)	30 (0)	30 (0)	5 (0)	30 (0)	54 (0)	2 (0)	100 (−42)
Albuquerque	54 (6)	1 (0)	30 (0)	30 (0)	4 (1)	30 (0)	52 (4)	1 (0)	114 (84)
Chicago	76 (0)	1 (0)	30 (0)	30 (0)	4 (0)	30 (0)	68 (−2)	1 (0)	126 (−12)
Burlington	76 (−4)	1 (0)	30 (0)	30 (0)	5 (0)	30 (0)	58 (−2)	2 (0)	72 (−18)
Duluth	74 (0)	1 (0)	30 (0)	30 (0)	4 (0)	30 (0)	68 (0)	1 (0)	86 (−4)

PV system. Since the change of one unit in the number of wind systems is going to greatly influence the power output of the RE system, we don't rank the building in each city with RE systems prioritized by wind systems. After averaging the numbers in B1 and A2 and calculating the percentage change, the results are presented in Table 13.

$$C_{change\%} = \frac{C_{future} - C_{TMY}}{C_{TMY}} \times 100\% \tag{25}$$

where, $C_{change\%}$ is the percentage change of subsystem's configuration; C_{future}, C_{TMY} are the configuration of subsystem under future, and present climate condition respectively that enables the building to meet the NZEB target. In Table 13, the cities are ranked with their average percentage change of the least number of PV panels under B1 and A2 compared with the reference climate. The degree of vulnerability to GCC rises with the absolute value of the positive percentage. For example, the results show that the present day's NZEB in Albuquerque (4B climate zone) is the most vulnerable to climate change, and that in San Francisco it is the least vulnerable one.

Table 13
RE system vulnerability rank.

City	Percentage change in PV panel number
Albuquerque	12.50
Memphis	4.69
Miami	3.33
Phoenix	3.13
Duluth	2.70
Chicago	−1.32
Philadelphia	−1.43
Houston	−2.94
Burlington	−6.25
San Francisco	−11.11

6. Conclusions

This paper posed the problem of the vulnerability to climate change impacts of present configurations of renewable energy systems designed to achieve net-zero energy buildings (NZEB), presents an analytical method for predicting the degree of this vulnerability, and uses this method for buildings in 10 US climatic regions. The NZEB in this research is defined as net source energy zero building which is justified by the annual source energy zero balance. The time series method described by Belcher et al. [33] is used for downscaling the HadCM3 model output into local hourly weather information during the years 2040–2069 for the B1 and A2 SRES (the IPCC Special Report: Emission Scenarios). To avoid abnormal weather conditions in a specific year, we averaged the weather variables throughout years 2040–2069 and then generated representative weather files as inputs to the EnergyPlus building energy analysis software. The downscaling results show that the trend magnitudes of temperature change in various climate zones are different, which makes it hard to draw a generalized pattern of the climate change impact on local weather variables. Building models with different thermal properties and system sizings are used in each climate zone to predict the future energy load in hourly granularity. Since the lighting and other equipment's energy use in the building are comparatively stable, the changes in the electricity and thermal energy is mainly due to cooling and heating load changes, For most cities, the electricity use will increase in the future, while the thermal load is not always decreasing in the future, implying more complex future climate condition, with more extremeness, thus making it hard to draw simple conclusions or develop laws on future building's energy design and use. It is important to be noted that this study is carried out based on the presumption that building retrofit is not going to take place in the future.

The modeling and coupling of renewable energy system and building load was conducted by establishing connections with the hourly energy load of the building and the hourly renewable energy resources including solar radiation, outdoor temperature, and wind speed. We designed a grid search method to quickly find the RE system with the "least" subsystem resource (numbers of PV panels, wind systems, and solar thermal collectors) to meet the NZEB criterion under certain climate scenarios provided with a certain design space. We also designed a grid search method for finding the RE systems with different relative shares of PV, solar heat collectors, and wind power for each building. The main findings for the performance of future NZEB in each climate zone are:

- An NZEB is defined in this paper as a building that achieves annual balance between source energy use and generation. Buildings in half of the ten climate zones will miss the target of meeting net zero energy in the future GCC climate scenarios. The climate-driven change in heating and cooling energy demand is the main driver for that failure. The most vulnerable case is the building in Albuquerque, which has a huge deficit in source energy balance.
- Among all the NZEBs in the ten climate zones, in the future, the proportion of decreased annual PV output is 5 out of 20 (10 cities $\times$ 2 future climate scenario), while that of wind systems is 12 out of 20, indicating the comparatively lower stability of the RE system prioritized to wind than prioritized to PV.
- In most climate zones, the energy output of the PV panel system will be increasing in the future, showing that the PV panel system is a reliable onsite renewable energy system not only at present, but also in the future.
- The RE system configuration should be designed with care in places with large diurnal and seasonal temperature variation (e.g., Phoenix, Albuquerque), and in places with very low number of heating degree-days and high cooling degree-days (e.g., Miami) because future climate is going to show more extremeness in temperature in these places.
- The sizing and configuration of future NZEB will be different from the present, and using the grid search method proposed in this paper under future SRES, one can find the net zero energy goal fulfilling system configuration. Moreover, the vulnerability of the NZEB in present days to future GCC can be quantified as shown in this paper by the percentage change of PV panels in the new configuration that meets NZEB target.

The limitation of this study mainly involves the uncertainties of future climate scenarios. In addition, more detailed research is needed on the impact of possible building retrofit during the climate change period on the vulnerability or resistance of the present NZEB to future climates, including better design and energy efficient measures related to building envelope, building system, and occupancy behavior.

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