Impacts of climate change and its uncertainties on the renewable energy generation and energy demand in urban areas

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Vahid M. Nik[1,2,3,*], Yuchen Yang[1], Bijan Adl-Zarrabi[2]

[1]Division of Building Physics, Department of Building and Environmental Technology, Lund University, Lund, Sweden
[2]Division of Building Technology, Department of Civil and Environmental Engineering, Chalmers University of Technology, Gothenburg, Sweden
[3]Institute for Future Environments, Queensland University of Technology, Brisbane, Australia

[*] *vahid.nik@byggtek.lth.se*

ABSTRACT
This work investigates the effects of future climate uncertainties in calculating the heating and cooling demand of buildings and estimating potentials for renewable energy generation (solar PV and wind). The building stock of Lund in Sweden is considered for energy simulations and for future climate, the most recent outputs of RCA4, which is the 4th generation of the Rossby Centre regional climate model (RCM), is used considering several two representative concentration pathways (RCPs) and four global climate models (GCMs). Simulations and assessment are performed for three 30-year time periods, from 2010 until 2099. Through comparing distributions of data sets, it is found that the uncertainty induced by climate models affects the estimation of renewable energy generation more than those induced by time periods. Changes in the heating demand due to climate change and uncertainties are surprisingly low while it is very large for cooling demand. This can be because of having a good quality for buildings on the average, however this should be more investigated for other cities in Sweden.

KEYWORDS
Climate change; regional climate model; Future climate uncertainties; energy demand in urban areas; renewable energy generation;

INTRODUCTION
By the advances in climate simulation and numerical modelling, it is possible to make better estimating the probable future conditions, which helps a lot in energy and infrastructure planning. A large amount of work exists on assessing the impacts of climate change on buildings as the main energy users, considering different types of buildings, their characteristics and their thermal comfort, retrofitting and energy saving potentials (e.g. (de Wilde and Coley 2012) (Nik 2012)). More than the energy demand, climate change may also alter generation out of renewable sources such as wind, hydropower and solar energy (Nik 2016).

The common approach in the impact assessment for engineering applications is introducing future weather files into building simulations. One of the big difference is the source and type of the future weather file. The origin of most of the available future weather files (in any temporal and spatial resolutions) which are used for energy simulations, are global climate models (GCMs) – also known as the general circulation models –which simulate climatic conditions under different initial and boundary conditions. GCMs simulate future climatic conditions for the spatial scale of 100-300km^2 which is coarse for the purpose of impact assessment. Therefore, GCM data are downscaled by the means of statistical (such as morphing) or dynamic downscaling techniques. The latter is performed through using regional climate models (RCMs), which provide weather data with suitable temporal (down to 15 minutes) and spatial resolutions (down to 2.5km^2) for direct use in building and energy simulations. It is not possible to rely on short time spans in the impact assessment of climate change the considered span should be 20 to 30 years. Moreover, there are different uncertainties which affect simulated climate data, such as the selected GCM, RCM, emissions scenario (which is not used anymore by IPCC) or representative concentration pathways (RCPs) and the spatial resolution (Nik, Sasic Kalagasidis, and Kjellström 2012). This means that a valid assessment should consider several future climate scenarios. Therefore, one important challenge is dealing with large data sets and uncertainties ((Nik, Sasic Kalagasidis, and Kjellström 2012) (Nik 2010)). Uncertainties due to climate change have been considered in several works (e.g. (Nik 2010)).

This work investigates the impacts of climate change on the energy demand of buildings and the renewable energy generation out of solar PVs and wind turbines. In this respect, the building stock in Lund is modelled for six different climate scenarios. The same scenarios are used for estimating the potentials of renewable generation. More information about the climate models and energy calculations are provided under the methodology section and results discussed afterwards.

METHODOLOGY

This section briefly describes the energy and climate models and some of the equations which are used for renewable generation calculations. Since most of the theory part have been discussed in previously published works, the reader is referred to the major references. For all the calculations, hourly weather data sets from six climate scenarios have been used for three 30-year periods of 2010-2039, 2040-2069 and 2070-2099.

Climate models and future weather data sets

The weather data sets are synthesized version of RCA4 (Samuelsson et al. 2015), the 4th generation of the RCM by the Rossby Centre at Swedish Meteorological Hydrological Institute, with the spatial resolution of 12.5km resolution and the temporal resolution down to 15 minutes. RCA4 downscaled four GCMs: CNRM-CM5, ICHEC-EC-EARTH, IPSL-CM5A-MR and MPI-ESM-LR. The first two GCMs are forced by two Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5, and the other GCMs are forced only by RCP8.5. This gives six different climate scenarios for Lund. RCPs are four greenhouse gas concentration trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014. All the RCM weather data were synthesized in Matlab before being used in energy simulations. For more details the reader is referred to (Nik 2016) and (Nik 2010).

Energy demand simulation

The residential building stock in Lund, Sweden is modelled in Simulink/Matlab. Lund is one the major cities in southern Sweden with the area of 25.75 km^2 and the population of around 88790. The building stock of Lund is statistically represented by 52 buildings using the data sets by the the Swedish National Board of Housing, Building and Planning (Boverket), which is the major information source for the energy performance of buildings in Sweden and has been used previously in several works (e.g. (Nik 2012) (Nik and Sasic Kalagasidis 2013) (Nik et al. 2016)). Figure 1 shows distributions of the U-values, heated floor areas and window areas of the buildings. For more details about modelling and assessing the future energy performance of the building stock the reader is referred to (Nik 2012) and (Nik and Sasic Kalagasidis 2013).

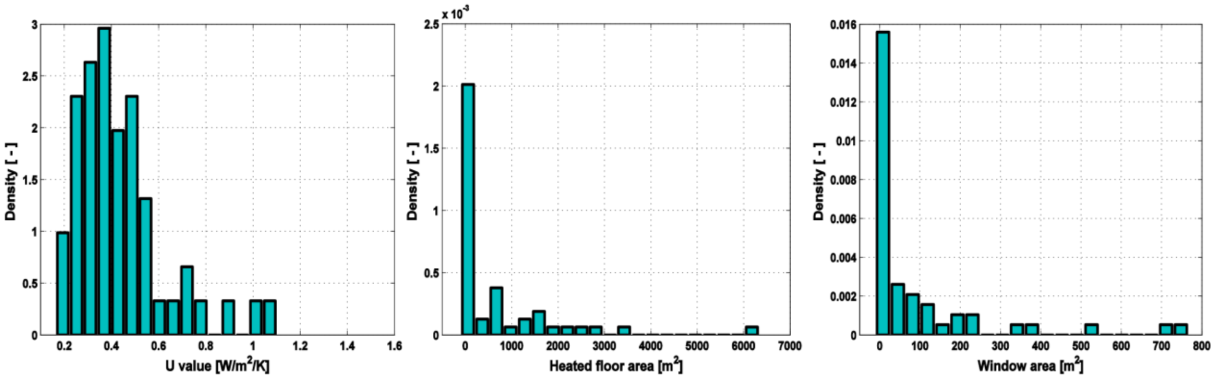

Figure 1. Distribution of the U values, heated floor areas and window areas of the building stock in Lund (figure is from (Nik 2012)).

Calculating the potentials for renewable generation

For comparing the effects of climate data uncertainties is estimating the solar energy potentials, the generated power from unit surface area (1 m^2) is calculated according to relation (1) (Zervas et al. 2008):

$$P = A(0.128G_T - 0.239 \times 10^{-3}T_a) \tag{1}$$

where, P is the generated electrical power [W], A is the aperture surface area of PV module [m^2], G_T is solar radiation flux (irradiance) on module plane [W/m^2] and T_a is the ambient temperature [K].

Wind power generation is calculated according to relation (2) (Perera et al. 2012):

$$\widetilde{P_w}(t) = \begin{cases} P_w = 0 & V < V_{ci} \\ P_w = aV^3 - bP_r & V_{ci} < V < V_r \\ P_w = P_r & V_r < V < V_{co} \\ P_w = 0 & V_{co} < V \end{cases} \tag{2}$$

where $\widetilde{P_w}$ is the power output from wind turbine [kW/m2], V is the wind speed at hub level [m/s] which is assumed 60 m, Vr, V_{ci} and Vco are respectively rated wind speed, cut in wind speed, cut off speed [m/s], Pr is rated power of the wind turbine [kW] which is assumed as 20. a and b are calculated as $a = P_r/(V_r^3 - V_{ci}^3)$ and $b = V_{ci}^3/(V_r^3 - V_{ci}^3)$.

RESULTS

Distributions for the heating and cooling demand of the building stock in Lund are shown in Figure 2 during 2070-2099. Differences due to climate change and its uncertainties are calculated in Table 1 and Table 2. Differences are visible and considerable in cooling demand; it can be even above 200% during 2070-2099 (depends on the climate scenario, e.g. 215% for ICHEC-rcp45 during 2070-2099) and depending on the selected climate scenario, differences (for one time period) can be also more than 200% (e.g. 234% for CNRM-rcp45 during 2010-2039 in Table 2). For Lund, which the cooling demand is much smaller than heating demand, differences between scenarios and time periods are quite negligible. This is in the contrary of the previous results using RCA3 (the older version of the RCM) which GCMs were forced by emissions scenarios defined by SRES IPCC (for more details, the reader is referred to (Nik 2012)(Nik and Sasic Kalagasidis 2013).

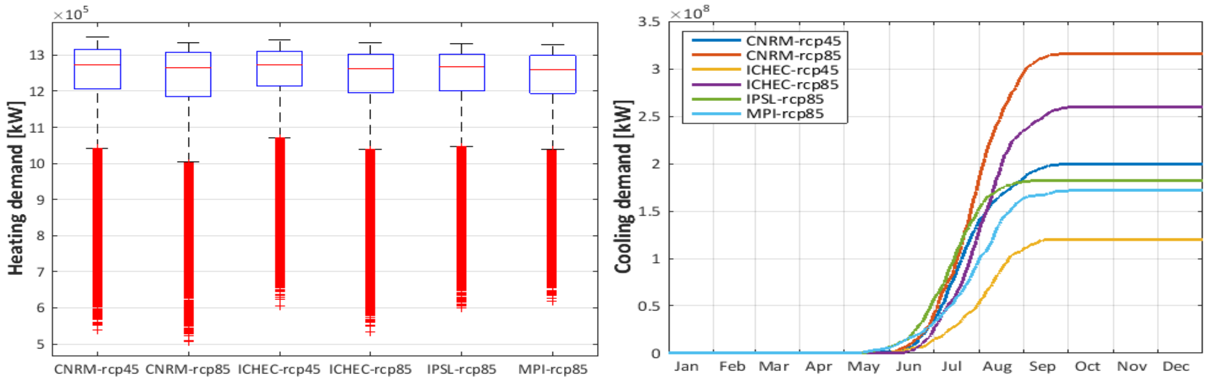

Figure 2. Distribution of the hourly heating demand (left) and cumulative cooling demand of the building stock in Lund for different climate scenarios during 2070-2099.

Table 1. Heating demand for different future climate scenarios.

Climate Scenarios	CNRM-rcp45	CNRM-rcp85	ICHEC-rcp45	ICHEC-rcp85	IPSL-rcp85	MPI-rcp85
Heating for 2010-2039 [kW]	10810408	10834448	10892567	10878912	10942434	10831818
Relative difference (RD) from 2010-2039 for each climate scenario [%]						
RD for 2040-2069	-0.5	-0.9	-0.6	-0.9	-0.7	-0.4
RD for 2070-2099	-0.8	-2.4	-1.0	-2.4	-2.1	-1.7
Relative difference (RD) of scenarios from IPSL-rcp85 for each time period [%]						
RD for 2010-2039	-1.2	-1.0	-0.5	-0.6	0.0	-1.0
RD for 2040-2069	-1.0	-1.2	-0.3	-0.7	0.0	-0.8
RD for 2070-2099	0.0	-1.3	0.6	-1.0	0.0	-0.6

Table 2. Cooling demand for different future climate scenarios.

Climate Scenarios	CNRM-rcp45	CNRM-rcp85	ICHEC-rcp45	ICHEC-rcp85	IPSL-rcp85	MPI-rcp85
Cooling demand for 2010-2039 [kW]	200277	182159	81052	82116	59964	87072
Relative difference (RD) from 2010-2039 for each climate scenario [%]						
RD for 2040-2069	17.1	15.2	39.0	49.0	53.7	15.8
RD for 2070-2099	-0.4	73.6	48.5	215.9	204.0	97.6
Relative difference (RD) of scenarios from IPSL-rcp85 for each time period [%]						
RD for 2010-2039	234.0	203.8	35.2	36.9	0.0	45.2
RD for 2040-2069	154.5	127.8	22.3	32.8	0.0	9.4
RD for 2070-2099	9.4	73.5	-33.9	42.3	0.0	-5.6

Impacts of climate change and its uncertainties on estimating the renewable energy potentials are presented in the following; Figure 3 and Table 3 show results for solar PV power generation and Figure 4 and Table 4 for wind turbine. Differences due to selection of the climate scenario are visible for both the renewable sources, affecting solar PV generation up to 20% (e.g. for ICHEC-recp45 during 2070-2099 in Table 3) and wind power up to 22% (e.g. CNRM-rcp45 during 2070-2099 in Table 4). According to all the scenarios, potentials for PV power generation will be less in future while for wind power, some scenarios predict higher potentials and some less. In general, differences due to time period (climate change) are smaller – which is around 8% at the maximum – than those induced by the selection climate scenario (climate uncertainty) – which is around 20% at the maximum. It is important to consider that these results can be highly dependent on the location and the considered time scale. In this work, all the calculations were done in the hourly time scale, however the relative differences have been calculated based on the annual production. These differences can vary if the time scale changes for example to seasonal.

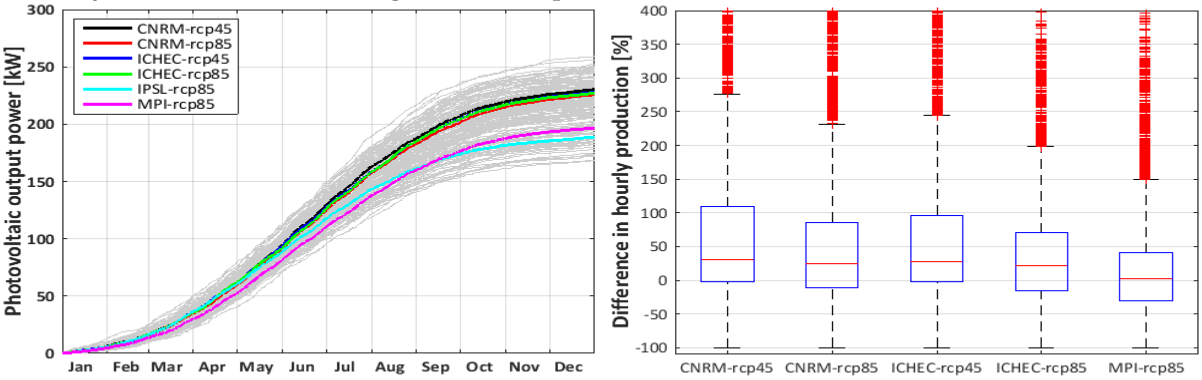

Figure 3. Cumulative solar PV power generation (left) and the relative differences on the hourly temporal resolution compared to IPSL-rcp85 (right).

Table 3. Solar PV power generation for different future climate scenarios.

Climate Scenarios	CNRM-rcp45	CNRM-rcp85	ICHEC-rcp45	ICHEC-rcp85	IPSL-rcp85	MPI-rcp85
PV power for 2010-2039 [kW]	238	240	235	229	204	213
Relative difference (RD) from 2010-2039 for each climate scenario [%]						
RD for 2040-2069	-2.4	-4.0	-0.7	-0.1	-2.6	-3.4
RD for 2070-2099	-3.3	-5.9	-3.0	-1.0	-7.6	-7.9
Relative difference (RD) of scenarios from IPSL-rcp85 for each time period [%]						
RD for 2010-2039	16.4	17.4	14.8	12.2	0.0	4.4
RD for 2040-2069	16.6	15.7	17.0	15.0	0.0	3.5
RD for 2070-2099	21.9	19.6	20.6	20.2	0.0	4.1

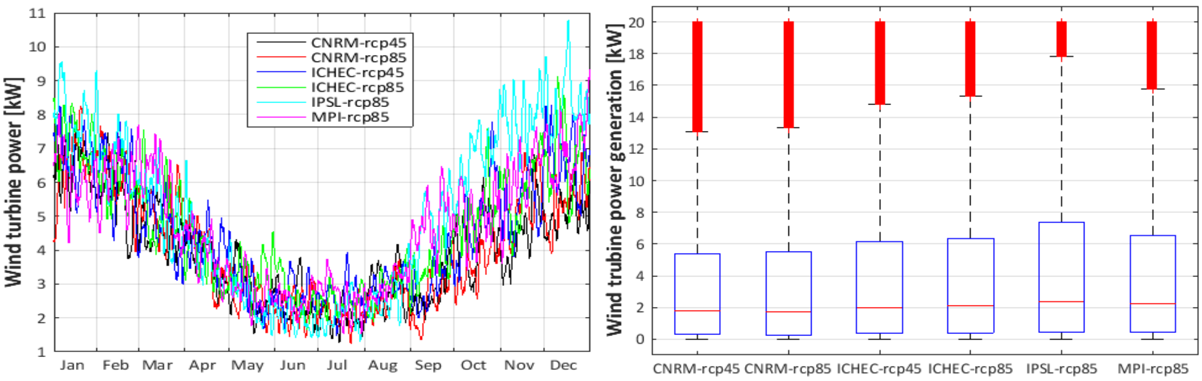

Figure 4. Wind power generation in hourly temporal scale for different climate scenarios.

Table 4. Wind power generation for different future climate scenarios.

Climate Scenarios	CNRM-rcp45	CNRM-rcp85	ICHEC-rcp45	ICHEC-rcp85	IPSL-rcp85	MPI-rcp85
Wind power for 2010-2039 [kW]	35166	36260	41232	40617	41077	38811
Relative difference (RD) from 2010-2039 for each climate scenario [%]						

RD for 2040-2069	-2.0	1.5	0.5	-0.8	4.7	-1.4
RD for 2070-2099	-2.0	-3.2	-6.3	-1.9	7.7	5.2
Relative difference (RD) of scenarios from IPSL-rcp85 for each time period [%]						
RD for 2010-2039	-14.4	-11.7	0.4	-1.1	0.0	-5.5
RD for 2040-2069	-19.9	-14.4	-3.6	-6.3	0.0	-11.1
RD for 2070-2099	-22.1	-20.7	-12.6	-9.9	0.0	-7.7

CONCLUSION AND DISCUSSION

According to the results, differences induced by climate change and its uncertainties in the cooling demand of buildings are very large, while there are negligible for heating demand of the building stock. The latter is contrary to the calculations using the older version of the climate model and should be investigated in more detail. Effects of climate change and uncertainties are visible in the renewable energy calculations, inducing differences up to 20% due to climate uncertainties and up to 8% due to climate change. In general, scenario point to less potential for renewable generation from solar PVs while for the wind turbine, numbers do not change considerably.

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