



CHALMERS
UNIVERSITY OF TECHNOLOGY

The impact of climate change on future Swedish heating and cooling demand

Master's thesis in Sustainable Energy Systems

ALICE ABRAHAMSSON

MASTER'S THESIS 2020

**The impact of climate change on future Swedish heating
and cooling demand**

ALICE ABRAHAMSSON



CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Space, Earth and Environment
Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

The impact of climate change on future Swedish heating and cooling demand
ALICE ABRAHAMSSON

© ALICE ABRAHAMSSON, 2020.

Supervisor: Emil Nyholm, Department of Space, Earth and Environment
Examiner: Lisa Göransson, Department of Space, Earth and Environment

Master's Thesis 2020:NN
Department of Space, Earth and Environment
Division of Energy Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Typeset in L^AT_EX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2020

Abstract

The impact of the future climate is highly uncertain and depends on aspects such as future emission pathways and climate sensitivity. Today the average global temperature has already increased by 1°C, with the increase being even higher in Sweden [1]. Global warming influence weather parameters which in turn impacts other parameters such as biomass growth and power generation from renewable energy sources, but it also impacts the heating and cooling sector on the demand side.

This thesis investigates how climate change impacts the Swedish heating and cooling demand by using an energy balance model to calculate how much energy is required to sustain an allowed indoor air temperature. The input to the model is a constant building stock and climate data regarding three different kinds of climates, the current climate, the climate at 1.5°C and 2°C average global temperature increase. The building stock data comes from the Swedish National Board of Housing's project, BETSI and the climate data comes from different climate models from the World Climate Research Programme, CORDEX. The minimum allowed indoor air temperature is defined by guideline values from the Swedish National Board of Housing. Since there are no technical standards regarding maximum indoor air temperature in buildings in Sweden, the incentives for implementing a cooling system is based on health guidelines for indoor air temperature. From the output of the energy balance model results that indicates how the heating and cooling system could be affected by climate change are generated.

The results show that the overall heating demand will be decreased between 5-13 % (-8.5 TWh) compared to the current scenario if the average global warming temperature is increased by 1.5°C and between 11-16% (-12 TWh) if the temperature is increased 2°C. The largest seasonal change occurs during winter time, and the smallest during the summer time. The cooling demand is increased with an increased average global temperature. At 1.5° average global temperature increase the cooling demand is increased 9-34% (+1.75 TWh) and at 2°C 10-40% (+2.25 TWh). The peak demand is slightly less affected by the changed climate compared to the yearly demand. There is a small change in the length of the heating period. In climate scenario 1.5°C the heating period is decreased 1.4-1.6% and in the 2°C climate scenario 2.1-2.2% demand decrease compared to the current climate scenario.

Acknowledgements

I would like to thank Lisa Göransson for the opportunity to do this work. I am very grateful for this experience.

I am very thankful for my supervisor Emil Nyholm who has shared his knowledge and also helped me stay motivated throughout this thesis work. Thank you for all your help.

A big thanks to Jenny Gode and Annamaria Sandgren at IVL, Swedish environmental institute for your input, support and guidance.

I would like to thank the World Climate Reseach Programme for providing their results from the climate models to the public.

Finally I would like to thank my husband and my family for their patience and support during the writing of this thesis.

Contents

1. Introduction	1
1.1. Background	2
1.1.1. Previous work	3
1.2. Aim and Scope	4
2. Method	5
2.1. Energy balance model	5
2.1.1. Introduction to the model	5
2.2. Climate data	8
2.3. Building stock data	11
2.4. Output from the model	13
3. Result	18
3.1. Introduction to result figures and total yearly heating demand	18
3.1.1. Total yearly heating demand	19
3.2. Heating demand in the building stock	21
3.2.1. Yearly peak heating demand	21
3.2.2. Yearly regional heating demand	23
3.2.3. Yearly peak heating demand per region	26
3.2.4. Seasonal changes to the heating demand	28
3.3. Cooling demand in the building stock	30
3.3.1. Total yearly cooling demand	30
3.3.2. Yearly peak cooling demand	32
3.3.3. Yearly regional cooling demand	36
3.3.4. Yearly maximum cooling effect per region	40
3.3.5. Seasonal changes to the cooling demand	44
3.4. Heating period	47
3.5. Demand changes in the different models	48
4. Discussion	51
4.1. Assumptions and limitations	51
4.1.1. Building stock data	51
4.1.2. Climate models	52
4.1.3. Cooling demand	52
4.1.4. The energy balance model	53
4.2. Comparison to the old study	54
4.3. Energy performance targets of buildings	54
4.4. Future research	54

5. Conclusion		55
References		57
A. Appendix 1		I
A.1. Total yearly heating demand		I
A.2. Total heating demand per season		VII
A.3. Total yearly cooling demand		IX
A.4. Total cooling demand per season		XV
A.5. Total yearly cooling demand including ventilation through windows . . .		XVII
A.6. Total cooling demand per season including ventilation through windows .		XXIII
A.7. Max effect heating demand		XXV
A.8. Peak cooling demand excluding ventilation through windows		XXXIV
A.9. Peak cooling demand including ventilation through windows		XLIII
A.10. Peak cooling demand per season including ventilation through windows .		L
A.11. Heating period		LII
B. Difference between models		LIV

List of Figures

1.	Energy use for heating and hot water in Swedish single- and multi-family dwellings and non-residential buildings during 1984-2018 [2]	2
2.	Energy balance of a building showing the different energy flows affecting the indoor air temperature. The different heat gains and losses are listed in Table 1	7
3.	Map of the NUTS2 division, which are the different regions that the SFD and MFD are divided into when the regional calculations are done.	14
4.	Total yearly heating demand in the Swedish building stock for the different climate scenarios and the different climate models. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	18
5.	Total yearly heating demand in the Swedish building stock per heated floor area for the different climate scenarios and the different climate models. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	21
6.	Yearly peak heating demand in Sweden for different models in the current, 1.5°C and 2°C climate scenarios. The black horizontal line marks the 30-year average of yearly peak demand in the current scenario, the dark red is the average in the 1.5°C scenario and the light red line is the peak demand in the 2°C scenario.	22
7.	4% of the yearly highest peak heating demand in Sweden. The different plots show how the climate is affecting 100%, 99%, 98% and 97% highest peak heating demand.	23
8.	Total yearly heating demand per square meter in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	24
9.	Total yearly heating demand in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	25
10.	Total yearly heating demand per area unit in the different regions, R1, R2 and R3, only including NRB. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	26

11.	The yearly peak heating demand in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD. The black horizontal line marks the 30-year average of yearly peak demand in the current scenario, the dark red is the average in the 1.5°C scenario and the light red line is the peak demand in the 2°C scenario.	27
12.	The yearly peak heating demand per area unit in the different regions, R1, R2 and R3, only including NRB. The black horizontal line marks the 30-year average of yearly peak demand in the current scenario, the dark red is the average in the 1.5°C scenario and the light red line is the peak demand in the 2°C scenario.	28
13.	Total heating demand during different seasons for the current, 1.5°C – RCP 2.6, 1.5°C – RCP 8.5 and 2°C – RCP 8.5 climate scenarios. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	29
14.	Peak heating demand during different seasons for the current, 1.5°C – RCP 2.6, 1.5°C – RCP 8.5 and 2°C – RCP 8.5 climate scenarios. The black horizontal line marks the 30-year average of yearly seasonal peak demand in the current scenario, the dark red is the average in the 1.5°C scenario and the light red line is the peak demand in the 2°C scenario.	30
15.	Total yearly cooling demand per m ² for the current, 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	31
16.	Total yearly cooling demand per m ² including cooling through windows for the current, 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	32
17.	Yearly peak cooling demand per m ² without cooling through windows for the current, 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. The black horizontal line marks the 30-year average of yearly peak demand in the current scenario, the dark red is the average in the 1.5°C scenario and the light red line is the peak demand in the 2°C scenario.	33

-
18. Yearly peak cooling demand per m² including ventilation through windows for the current, 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. The black horizontal line marks the 30-year average of yearly peak demand in the current scenario, the dark red is the average in the 1.5°C scenario and the light red line is the peak demand in the 2°C scenario. 34
 19. 4% of the yearly highest peak cooling demand in Sweden. The different plots show how the climate is affecting 100%, 99%, 98% and 97% highest peak cooling demand for the 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. 35
 20. 4% of the yearly highest peak cooling demand in Sweden when including ventilation through windows. The different plots show how the climate is affecting 100%, 99%, 98% and 97% highest peak cooling demand for the 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. 36
 21. Total yearly cooling demand per area unit for regions SE1, SE2, SE3 and SE4. Excluding ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. 37
 22. Total yearly cooling demand per area unit for regions SE1, SE2, SE3 and SE4. Including ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. 38
 23. Total yearly cooling demand per area unit for regions R1, R2 and R3. Excluding ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. 39
 24. Total cooling demand per area unit for regions R1, R2 and R3. Including ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. 40
 25. Yearly peak cooling demand per area unit for regions SE1, SE2, SE3 and SE4. Excluding ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. 41

26.	Yearly peak cooling demand per area unit for regions SE1, SE2, SE3 and SE4. Including ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	42
27.	Yearly peak cooling demand per area unit for regions R1, R2 and R3. Excluding ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	43
28.	Yearly peak cooling demand per area unit for regions R1, R2 and R3. Including ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	44
29.	Total cooling demand during different seasons per area unit excluding ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	45
30.	Total cooling demand during different seasons per area unit including ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	46
31.	Peak cooling demand during different seasons excluding ventilation through windows per area unit. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.	47
32.	Length of heating period for four different climate scenarios. (Note that the y-axis does not start at 0)	48
33.	The degree of changed demand for the different models compared to the current demand for each model. The first box is the total heat demand, the second is the cooling demand and the last box is the cooling demand including ventilation through windows. The first scenario in every box is the demand at a global temperature increase of 1.5°C in the RCP 2.6 scenario, the second is 1.5°C temperature increase at RCP 8.5 and the last is 2°C temperature increase at RCP 8.5.	49

-
34. The degree of changed maximum effect for the different models compared to the current maximum effect for each model. The first box is the maximum heat effect, the second is the maximum cooling effect and the last box is the maximum cooling effect including ventilation through windows. The first scenario in every box is the maximum effect at a global temperature increase of 1.5°C in the RCP 2.6 scenario, the second is 1.5°C temperature increase at RCP 8.5 and the last is 2°C temperature increase at RCP 8.5. 50
35. Total yearly heating demand in the Swedish building stock for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. I
36. Total yearly heating demand in the Swedish building stock per heated floor area for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. II
37. Total yearly heating demand in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. III
38. Total yearly heating demand per heated floor area in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. IV
39. Total yearly heating demand in the different regions R1, R2 and R3, only including NRB, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. V

- 40. Total yearly heating demand per heated floor area in the different regions R1, R2 and R3, only including NRB, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. VI
- 41. Total seasonal heating demand in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. VII
- 42. Total seasonal heating demand per heated floor area in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. VIII
- 43. Total yearly cooling demand in the Swedish building stock for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows. IX
- 44. Total yearly cooling demand in the Swedish building stock per heated floor area for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows. . . . X
- 45. Total yearly cooling demand in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows. XI

-
46. Total yearly cooling demand per heated floor area in the different regions SE1, SE2 SE3 and SE4, only including SFD and MFD for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows. XII
 47. Total yearly cooling demand in the different regions R1, R2 and R3, only including NRB for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows. XIII
 48. Total yearly cooling demand per heated floor area in the different regions R1, R2 and R3, only including NRB for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows. XIV
 49. Total seasonal cooling demand in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows. . . . XV
 50. Total seasonal cooling demand per heated floor area in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows. XVI
 51. Total yearly cooling demand in the Swedish building stock including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XVII

-
52. Total yearly cooling demand in the Swedish building stock per heated floor area including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XVIII
53. Total yearly cooling demand including natural ventilation in the different regions SE1, SE2, SE3 and SE3, only including SFD and MFD and including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XIX
54. Total yearly cooling demand heated floor area in the different regions, only including SFD and MFD and including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XX
55. Total yearly cooling demand in the different regions R1, R2 and R3, only including NRB and including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXI
56. Total yearly cooling demand per heated floor area in the different regions R1, R2 and R3, only including NRB and including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXII
57. Total seasonal cooling demand in the winter, spring, summer and fall season, including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXIII

-
58. Total seasonal cooling demand per heated floor area in the winter, spring, summer and fall season, including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXIV
59. Yearly peak heating demand in the Swedish building stock for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXV
60. Yearly peak heating demand in the Swedish building stock per heated floor area for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXVI
61. 4% of the yearly highest peak heating demand in the Swedish building stock. The different plots show how the climate is affecting 100%, 99%, 98% and 97% highest peak heating demand for the 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. XXVII
62. Yearly peak heating demand in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXVIII
63. Yearly peak heating demand per heated floor area in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXIX
64. Yearly peak heating demand in the different regions R1, R2 and R3, only including NRB for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXX

- 65. Peak heating demand per heated floor area in the different regions R1, R2 and R3, only including NRB for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXXI
- 66. Peak seasonal heating demand in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXXII
- 67. Peak seasonal heating demand per heated floor area in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXXIII
- 68. Yearly peak cooling demand in the Swedish building stock excluding ventilation through windows, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXXIV
- 69. Yearly peak cooling demand in the Swedish building stock per heated floor area excluding ventilation through windows, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXXV
- 70. 4% of the yearly highest peak cooling demand in the Swedish building stock when excluding ventilation through windows. The different plots show how the climate is affecting 100%, 99%, 98% and 97% highest peak cooling demand for the 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. XXXVI

-
71. Yearly peak cooling demand in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD and excluding ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXXVII
 72. Yearly peak cooling demand per heated floor area in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD and excluding ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXXVIII
 73. Yearly peak cooling demand in the different regions R1, R2 and R3, only including NRB and excluding ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XXXIX
 74. Yearly peak cooling demand per heated floor area in the different regions R1, R2 and R3, only including NRB and excluding ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XL
 75. Peak seasonal cooling demand in the winter, spring, summer and fall season, when excluding ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XLI
 76. Peak seasonal cooling demand per heated floor area in the winter, spring, summer and fall season, when excluding ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XLII

-
77. Yearly peak cooling demand in the Swedish building stock including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XLIII
78. Yearly peak cooling demand in the Swedish building stock per heated floor area including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XLIV
79. 4% of the yearly highest peak cooling demand in the Swedish building stock when including ventilation through windows. The different plots show how the climate is affecting 100%, 99%, 98% and 97% highest peak cooling demand for the 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. XLV
80. Yearly peak cooling demand including ventilation through windows in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XLVI
81. Yearly peak cooling demand per heated floor area including ventilation through windows in the different regions SE1, SE2 SE3 and SE4, only including SFD and MFD for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XLVII
82. Yearly peak cooling demand including ventilation through windows in the different regions R1, R2 and R3, only including NRB for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XLVIII

-
83. Peak cooling demand per heated floor area including ventilation through windows in the different regions R1, R2 and R3, only including NRB for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. XLIX
84. Peak seasonal cooling demand including ventilation through windows in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. L
85. Peak seasonal cooling demand per heated floor area including ventilation through windows for the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. LI
86. Heating period for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average length of the heating period in the current scenario, the dark red line is the average length in the 1.5°C scenario and the light red line is the average length in the 2°C scenario. (Note that the y-axis does not start at 0) LII
87. Heating period for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario at three different definitions of start and end points, 1%, 2% and 3%. The black horizontal line marks the average length of the heating period in the current scenario, the dark red line is the average length in the 1.5°C scenario and the light red line is the average length in the 2°C scenario. (Note that the y-axis does not start at 0) LIII
88. The degree of changed demand for the different models compared to the current demand for each model. The first box is the total heat demand, the second is the cooling demand and the last box is the cooling demand including ventilation through windows. The first scenario in every box is the demand at a global temperature increase of 1.5°C in the RCP 2.6 scenario, the second is 1.5°C temperature increase at RCP 8.5 and the last is 2°C temperature increase at RCP 8.5. LIV

89. The degree of changed maximum effect for the different models compared to the current maximum effect for each model. The first box is the maximum heat effect, the second is the maximum cooling effect and the last box is the maximum cooling effect including ventilation through windows. The first scenario in every box is the maximum effect at a global temperature increase of 1.5°C in the RCP 2.6 scenario, the second is 1.5°C temperature increase at RCP 8.5 and the last is 2°C temperature increase at RCP 8.5. . LV

List of Tables

- | | | |
|----|--|----|
| 1. | List of buildings' heat gains and losses included in the energy balance model. | 6 |
| 2. | List of climate models from CORDEX used in the thesis. The years listed in the table marks the middle of the 30 year period when the different levels of global warming occur. | 10 |
| 3. | Building stock parameters from the BETSI study | 12 |
| 4. | List of the result parameters of interest and the different levels of geographical and temporal detail they are presented as. | 15 |

1. Introduction

As of 2018 the global temperature average has increased by 1°C compared to pre-industrial levels, with the increase in Sweden being even higher [1]. The intensity of future climate change is highly uncertain and depends on a large variety of different parameters such as climate sensitivity and future emission pathways. The long-term change in weather parameters due to climate change can have an impact on the current and future Swedish energy infrastructure and demand. This thesis will investigate how the future climate will impact the Swedish building stocks' heating and cooling demand depending on different levels of global warming.

EU states that around 36% of the total CO₂ emissions in the member states comes from energy use in the building stock sector [3]. Energy use in buildings is therefore a hot topic in the transition to a renewable energy system. To be able to make the transition and create a sustainable energy system that can supply the demand at all times it is important to have an estimation of what the future heating and cooling demand could look like. If preparations are done the risks of the system being unqualified for future situations are smaller.

Linked to the transition to a fossil free energy systems and the future demand is also the aspect of profitability. 46% of the Swedish heating demand is satisfied by district heating systems today [3]. The installation of a new district heating system or a renovation of an existing system is very costly, but when established they have a long lifetime and are very cheap to operate. Besides the large investment cost, they only operate during the time of the year where there is a demand for comfort heat, which means they only generate profit during part of the year. Since there are very large investment costs associated with implementing or updating a district heating system there must be a demand for comfort heat in the years to come to be able to cover the investment. If it is no or low demand for heat in the future or only during short periods of time every year, the incentives to expand and update the existing system further are low, but if the demand of comfort heat increases the incentives increases as well.

A technology that also works well in a renewable energy system is different kinds of individual heat pumps. Heat pumps are getting more and more efficient and are starting to be a serious competitor to the district heating system. If the demand for cooling increases, air-to-air heat pumps will probably get more and more popular since they can be reversed to cool down buildings during the warmer months.

1.1. Background

The Swedish Energy Agency states that the total amount of heating was in total 79 TWh during 2018 [4]. The most common heating source for single-family dwellings(SFD) was electricity by heat pumps, electric boilers or direct electricity [4]. The second most common source was biomass. For multi-family dwellings(MFD) and non-residential buildings(NRB) the most common heating technology was district heating [4]. In Figure 1 the energy used for heating and hot water in buildings during 1984-2018 can be seen [4]. The heating demand has decreased from around 100 TWh to around 80 TWh during the 35 years' period in the Figure. The reason for this is probably due to a combination of different things, mainly a more energy efficient building stock, but also an increased amount of heat generating technology existing in every building, such as computers, kitchen appliances, entertainment equipment and more.

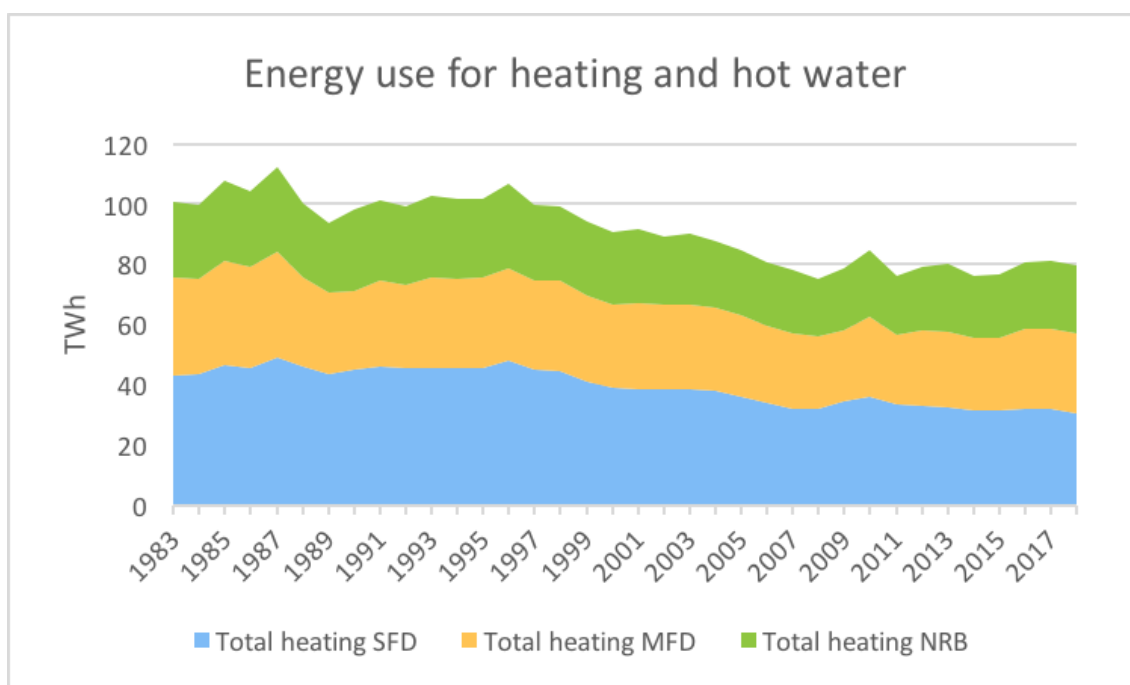


Figure 1: Energy use for heating and hot water in Swedish single- and multi-family dwellings and non-residential buildings during 1984-2018 [2]

Heat pumps have become more and more common and the Swedish Energy Agency states that this has helped to decreased the amount of energy supplied to the buildings since it uses the available heat on site [4].

In a summary of the energy use in non-residential buildings the Swedish Energy Agency

states that the energy used for comfort cooling is 79 kWh/m² [5]. Since comfort cooling is not very common in Swedish residential buildings the Swedish Energy Agency does not have any data regarding cooling systems in SFD and MFD.

1.1.1. Previous work

There are many different studies made that investigates the heating and cooling demand in buildings. Yi et al. investigated the cooling demand for different neighborhoods in Seoul using archetype buildings and archetype weather parameters as inputs to a model [6]. Yi et al. concluded that with no change in the building stock the maximum month cooling demand would increase 56%, 86% and 155% in their three different cases. Dobosi et al. calculated the heating and cooling demand of a hospital building using EnergyPlus simulation software and investigated how different Romanian climate locations affected the demand [7]. The input to the simulations were technical data specific to the hospital building and typical weather data connected to each climate region [7]. Li et al. also used EnergyPlus to investigate the implementation of a heating and cooling system in a hot summer and cold winter zone in south of China [8].

There are also many studies made regarding the Swedish heating and cooling demand. In 2007 Energiforsk released a large study with the aim of investigating the need of making the electricity system less weather sensitive [9]. As a part of that study the heating and cooling demand was investigated by considering the changed number of degree days between the period of 1960-1990 and 2011-2040 for three different cities in Sweden [9]. The conclusion from the study was that the increased numbers of high degree days due to a changed climate would have large impacts on the energy system because of a lowered heating demand and the possibility of an increased cooling demand [9].

Nik et al. made a study, called "Impact study of the climate change on the energy performance of the building stock in Stockholm considering four climate uncertainties", where different climate scenarios were included [10]. The study used 153 model buildings together with climate data from global and regional climate models and an energy balance model. The conclusion was that the future heating demand would decrease around 30% in 2100 compared to before 2011 and the future cooling demand was low enough to be satisfied by natural ventilation. The models used in the study all increased between 2.5-4°C during the years 1961-2100.

Mata et al. states in the study "Economic feasibility of building retrofitting mitigation potentials: Climate change uncertainties for Swedish cities" a summary of studies that investigates heating and cooling demand in different types of buildings and building stocks [11]. The studies included in the summary do not include the building stock of a

entire country, but the building stock in specific cities or sample buildings. The different studies investigate the demand of heating and cooling at different time periods and not at different levels of global warming.

1.2. Aim and Scope

The aim of this thesis is to investigate how the heating and cooling demand in Sweden could be affected by different levels of global warming. The aim is to look at the change in total heating and cooling demand and the change in peak heating and cooling demand. The length of the yearly heating period is also considered, which is the period when the heating systems are operating. This is considered since the heating period could affect the heating and cooling technologies in the future Swedish energy system. To investigate the impact of climate change further, the result will be divided into different regions to see if there are any differences between different climate zones and to investigate regional changes in the demand. To get a better understanding of how the demand changes during the year the seasonal average will also be considered.

The different levels of global warming of interest in this thesis is the current level, which is defined as the climate in 1985, the 1.5°C and 2.0°C average global temperature increase. The goal is to see if there are any trends in how the demand depends on the different levels of global warming.

Economical aspects such as price curves will not be a part of this study. Neither are different strategies and technologies of satisfying the demand. The demand will be calculated using a constant building stock where no energy efficiency measures, renovations, demolitions or infills are taken under consideration.

The results from the thesis will be part of a larger project conducted by IVL Swedish Environmental Research Institute, Swedish Meteorological and Hydrological Institute (SMHI), Profu, and Chalmers. The project is called "Consequences of climate change on the energy system", further on referred to as KLIMPEN. The aim of KLIMPEN is to investigate the impact of climate change on several aspects of the Swedish energy system.

2. Method

To find the Swedish heating and cooling demand an energy balance model is applied over every building in the building stock. The model calculates the required energy needed to sustain an allowed indoor temperature at every time step for every building. Input to the model is climate data regarding outdoor temperature and solar radiation and building data including different thermal properties and geographical location of the buildings. In this thesis, there are three different climate scenarios of interest, the current, the 1.5°C and the 2.0°C average global temperature increase. The climate data for the different climate scenarios comes from five different climate models.

The following sections below, first present the energy balance model, after that the climate data and then the building stock data. The final section describes how the output from the model was used to generate the results.

2.1. Energy balance model

The energy balance model is a GAMS model which originally was developed in Simulink by Mata et al. [12]. The model has since then been used and developed in a variety of different projects [13]. The report "Calculation of energy use in the Swedish housing", by Mata et al., lists the overall calculations and assumptions in the model [14] and the thesis "The role of Swedish single-family dwellings in the electricity system", by Nyholm, [13] lists important developments to the model before it was used in this thesis.

In the report "A modelling strategy for energy, carbon and cost assessment of building stocks", Mata et al. uses comparative and empirical methods to verify that the results from the energy balance model are close to the reality [12]. Two comparative studies are made to an office building in Barcelona and a residential building in Köping. The result from the energy balance model was compared with result from other models that have been validated [12]. The comparison showed that the result from the energy balance model agreed with the results from the validated models [12].

2.1.1. Introduction to the model

The energy balance model creates an energy balance over a building and calculates the required amount of energy needed to sustain an allowed indoor temperature for every hour for that specific building. This is done for the entire building stock giving the energy demand for every hour and every building.

The energy balance can be seen in Figure 2, Table 1 shows the heat gains and losses in the energy balance. There are two different versions of the energy balance. One is a one-stage energy balance where the energy flows between the outside and the indoor air of the building. The second one is a two-stage energy balance where the building envelope is included in the heat transfer. The one-stage energy balance is a simplification of the two-stage energy balance, where less knowledge and data is required about the building investigated. The two-stage energy balance is more detailed and gives a result that is closer to the reality. See "The role of Swedish single-family dwellings in the electricity system" for further information about the energy balance mode [13].

Table 1: List of buildings' heat gains and losses included in the energy balance model.

Parameters	Description
q_app	Heat gains from appliances
q_buis	Heat gains/losses from ventilation system
q_cool	Cooling energy from cooling system
q_heat	Heating energy from heating system
q_light	Heat gains from lights
q_occ	Heat gains from occupants
q_r	Heat gains from solar radiation
q_vent	Heat gains/losses from ventilation
q_window	Heat losses from open windows

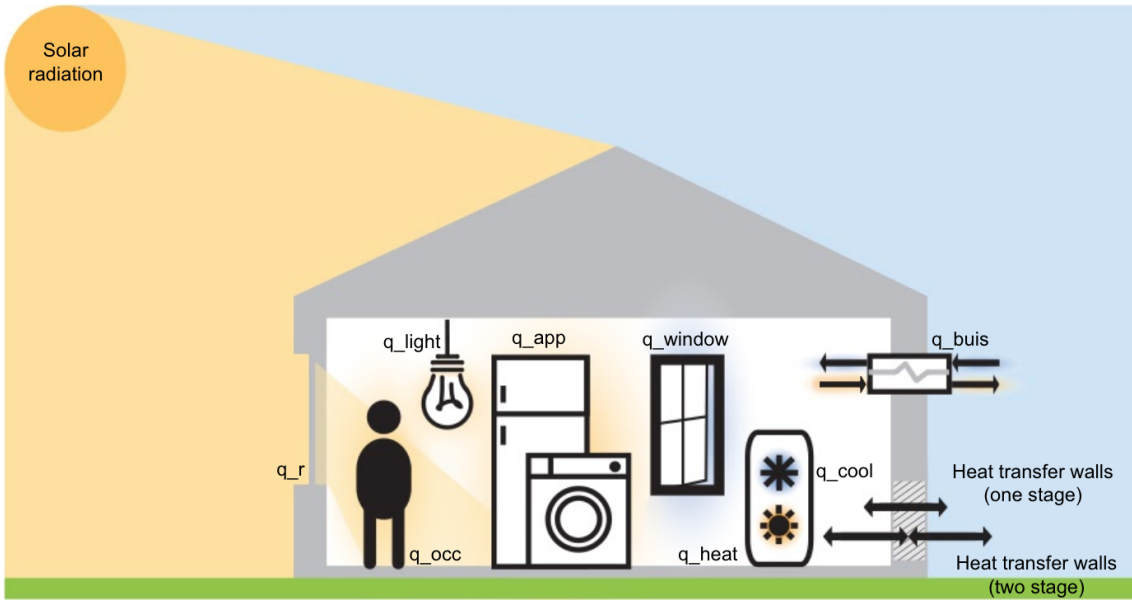


Figure 2: Energy balance of a building showing the different energy flows affecting the indoor air temperature. The different heat gains and losses are listed in Table 1

A big change in the model compared to the version used in Nyholm's thesis [13] is that the objective function is changed from optimizing for minimum cost to optimizing for minimum required amount of heating (q_{heat}) and cooling energy (q_{cool}) supplied to the building, see Equation 1 below. q_{tot} is the total energy supplied to every building (b) during one year where t is every time step.

$$\text{minimize } q_{tot} = \sum_{t,b} q_{heat}(t, b) + q_{cool}(t, b) \quad (1)$$

In Nyholm's thesis [13] the cooling demand is not calculated; therefore the calculation of the cooling demand is implemented in the model. There are no technical standards regarding maximum allowed indoor air temperature for Swedish buildings, but there are different health guide lines from organisations such as the Swedish Health Authority and the World Health Organisation (WHO). The Swedish Public Health Authority states that an indoor air temperature above 26°C is an inconvenience to human health [15]. This statement is used as the maximum allowed indoor air temperature in the model for buildings with an installed cooling system. For buildings without a cooling system a higher maximum value is used. WHO states that during heat waves it is very important to keep the indoor air below 32°C [16]. Since there are no standards regarding maximum indoor air temperature in Sweden it is up to the house owner to implement a cooling system. WHO's

recommendation is used in the model as the limit when the house owner feels incentives to invest in a cooling system. When the building reaches an indoor air temperature equal to or above 32°C a cooling system is implemented to that specific building in the model.

During summers the building can be warmer than the outside air. In some cases, the building can be cooled down enough by opening windows to air out the building. In cases like that a cooling system does not have to be running. Therefore Equation 2 below is added to the model which calculates the possible amount of cooling energy that can be supplied without using a cooling system. V_{cn} is the natural ventilation rate, $A_{building}$ is the area specific to each building, Cp_{air} is the specific heat capacity of air and T_{in} and T_{out} is the temperature of the indoor and outdoor air respectively.

$$q_{window} = V_{cn} * A_{building} * Cp_{air} * (T_{in} - T_{out}) \quad (2)$$

The climate data used as input to the model is the outdoor air temperature and the solar radiation at every third hour. To match the climate data the energy balance in the model is changed to sustain the indoor temperature for three hours at every time step instead of one. Equation 3 shows the original two stage equation and Equation 4 shows the new equation where the different heat gains and losses are multiplied by three. Meaning, the climate conditions at every time step are assumed to be constant during three hours.

$$T_{in_air}(t) = T_{in_air}(t - 1) + (q_{air_mass}(t) + q_{vent}(t) + q_{int}(t) + q_r(t) + q_{heat}(t) - q_{cool}(t)) * 3600 / TC_{air} \quad (3)$$

$$T_{in_air}(t) = T_{in_air}(t - 1) + 3 * (q_{air_mass}(t) + q_{vent}(t) + q_{int}(t) + q_r(t) + q_{heat}(t) - q_{cool}(t)) * 3600 / TC_{air} \quad (4)$$

2.2. Climate data

The climate data used in this thesis come from different climate model simulations from CORDEX, Coordinated Regional Climate Downscaling Experiment [17], which is part of the World Climate Research Programme (WCRP). The goal of the experiment is to create and improve regional climate projections [18]. A climate model consists of a global numerical climate model, which is also called "General circulation model" (GCM), and a "Regional climate model" (RCM). The GCM simulates the climate on a global scale with

a horizontal resolution between 100-500 km and 6-hour temporal frequency [17]. The RCM downscales the output from the GCM to get a 10-50 km horizontal resolution and 30 minutes' temporal frequency to be able to describe local consequences of the global change [17]. To save computer capacity the temporal resolution is not as fine as 30 minutes in this thesis, but instead 3 hours. The models used in the thesis belongs to the domain called EUR-11 which have the highest geographical resolution possible, to make sure to capture small regional effects.

The World Meteorological Organization (WMO) defines climate as: "the statistical description in terms of the mean and variability of relevant quantities of certain variables over a period of time", which is often referred to as "average weather" [19]. The period of time is defined by WMO as a 30-year period [17, 19].

WMO's definition of climate is used in this thesis to create different climate scenarios. The climate scenarios of interest are the climate at a global average temperature increase of 1.5°C, 2.0°C and the current climate which was defined as the climate for the period centered around 1985. The year that defines the current climate in this thesis is the same as in the rest of the KLIMPEN study. The average global temperature increase is defined by KLIMPEN as the global average temperature compared to the global average temperature in pre-industrial times, around 1861-1890.

The reason for investigating levels of global warming rather than what happens during specific time periods is because different models or scenarios reach different levels of global warming at different times. To compare a specific year would therefore be to look for similarities between different climates and it would not give an insight in how a specific global temperature change affects the system. Looking at the same level of global warming makes it possible to see if there are any correlations within the same level and if there are trends between different levels of global warming.

The output from the climate models consists of a large set of different climate parameters for surface and atmosphere variables assigned to different geographical locations [17]. The variables of interest were the near-surface air temperature (tas), and the surface downwelling shortwave radiation ($rsds$), also referred to as surface downwelling shortwave flux in air. These two variables are important input parameters in the energy balance model, see parameters q_r and T_{out} in section 2.1. These are the parameters that differs between the different scenarios.

When analysing results from climate models it is important to keep in mind that they are simplified versions of the real climate system [17]. The results from the different models will vary since they value different parameters in different ways and they use different numerical approaches [17]. The different climate models will not have the same projections

of the future. The best projections are made when results from as many climate models as possible are combined. If the same trend is found in the majority of models it is statistically correct to assume that the trend will be close to reality. However, due to time limitations in the master's thesis there are only five different climate models used to create scenarios for one historical case, also referred to as the current case, and two different future cases based on different representative concentration pathways (RCP). This decision was based on recommendations from the contact person at SMHI, who also recommended to include at least five different climate models.

Nikulin et al. made a study called "The effects of 1.5 and 2 degrees of global warming on Africa in the CORDEX ensemble" [20]. In the supplementary material to Nikulin et al.'s work information regarding what year different climate models reach different levels of global warming are listed. All five models selected for this thesis are listed in Nikulin et al.'s supplementary work and they all included results from RCP 2.6 and RCP 8.5. The RCP 2.6 scenario only reaches 1.5°C temperature increase, why it is only one RCP 2.6 scenario in this thesis. RCP 8.5 reaches both 1.5°C and 2°C temperature increase and therefore there are two RCP 8.5 scenarios.

Table 2 below describes the different models and scenarios used in this thesis and at what year they reach a certain temperature increase [20]. The names of the climate models are shortened in the following section. The MPI-M-MPI-ESM-LR models are referred to as the MPI models, MOHC-HandGEM2-ES are referred to as MOHC and CNRM-CERFACS-CNMR-CM5 are referred to as CERFACS.

Table 2: List of climate models from CORDEX used in the thesis. The years listed in the table marks the middle of the 30 year period when the different levels of global warming occur.

GCM	RCM	Historical	RCP 2.6		RCP 8.5	
		Current	1.5 °C	2.0°C	1.5°C	2.0°C
MPI-M-MPI-ESM-LR	RCA4	1985	2023	-	2018	2035
	RegCM4-6	1985				
MOHC-HadGEM2-ES	RCA4	1985	2029	-	2024	2037
	RegCM4-6	1985				
CNRM-CERFACS-CNRM-CM5	ALADIN63	1985	2040	-	2029	2043

As mentioned above every climate scenario is a 30-year period. The years stated in Table 2 above represent the year in the middle of a 30 year period. Looking at the years at the different levels of temperature increase for the RCP 8.5 scenario it becomes clear that there is quite a bit of an overlap between the 1.5°C - and 2.0°C period. This means that

the different scenarios will have a few years in common and the results for the different scenarios will overlap.

2.3. Building stock data

The following section describes data regarding the Swedish building stock and how it was used in the thesis.

The building stock data used in this thesis originally comes from a study conducted by The Swedish National Board of Housing (Boverket). The study is known as Buildings' Energy use, Technical Status and Indoor climate, or BETSI [21]. The study was made during 2007-2008 and covered 826 single-family dwellings (SFD), 560 multi-family dwellings (MFD) and 367 non-residential buildings (NRB). The buildings were chosen by Boverket using statistical methods to get a good representation of the different buildings in Sweden [21]. The data sets include the buildings' dimensions, thermal properties and the minimum allowed indoor air temperature. The sampled buildings were assigned weights to be able to scale up the sample to match to the entire Swedish building stock. The SFD and MFD had been assigned to 30 different locations in Sweden, which made it possible to connect every specific building to the climate that represent the environment where the building is placed.

The SFD data set has been updated during Nyholm's thesis [13] to match the 2016 building stock in Sweden. The MFD and NRB represents the building stock during 2006. The NRB data set was updated to match a master thesis study previously done by Grundsell [22]. Based on that same thesis, the assumption was made that all NRB have FTX-ventilation systems. The NRB did not have a specific location assigned to them, but they were assigned a climate zone defined by Boverket. Grundsell assigned the NRB to the biggest city in each climate zone, which was Umeå, Sundsvall and Stockholm [22]. The same method of assigning the locations to the NRB is used in this thesis to be able to match the different buildings to a representative climate, the climate data node closest to the assigned location.

The building stock is a constant parameter throughout all the different scenarios of this project. This to make sure that the observed changes only happens due to changes in the climate and not changes made to the building stock. In Table 3 the parameters used from the building stock data are listed.

Table 3: Building stock parameters from the BETSI study

Parameters	Description	Unit
A	Area	m ²
Ac	Specific heat gains from appliances	W/m ²
Cp	Specific heat capacity	J/kgK
high_temp	Maximum indoor temperature	K
high_temp_nc	Maximum indoor temperature without cooling system	K
house_to_reg	EDOP-reg or climate zone definition	-
Lc	Specific heat gains from electric lights	W/m ²
low_temp	Minimum indoor temperature for different types of buildings	K
Oc	Specific heat gains from people	W/m ²
Pfh	Specific heat gains from ventilation fans	W/m ²
S	Total exterior area of a building envelope	m ²
Sw	Total window area	m ²
TC	Thermal constant of building	
TC_air	Thermal constant of indoor air	
Tint	Initial indoor air temperature	K
Ts	Window solar transmittance	-
TypeofVentsyst	Type of ventilation system (FTX, no FTX...)	-
U	Mean U value of a building	W/m ² K
U_mass_air	The heat transfer coefficient between the air and the mass of the building	W/m ² K
Vc	Sanitary ventilation rate	l/s/m ²
Wc	Solar shading coefficient	-
Vcn	Natural ventilation rate	l/s/m ²
weights	Number of every specific building in the building stock	-
Wf	Part of the total window area covered by window frames	-

Other than the BETSI data there are profiles regarding heat gains from occupants, lights and appliances during different times of the day related to the building stock. More information regarding the profiles can be seen in Nyholm's work "Demand response potential of electrical space heating in Swedish single-family dwellings" [23].

The building stock data did not include which buildings had a cooling system installed

today. Since cooling in Sweden was not very common in year 1985, no cooling systems were assumed for the SFD and MFD while all the NRB were assumed to have cooling systems installed.

2.4. Output from the model

As previously mentioned the energy balance model calculates the required amount of energy needed to sustain an allowed indoor air temperature. The required amount of energy refers to the heating and cooling energy needed and the cooling that can be supplied by opening windows. This following section describes how the output from the energy balance model is used to generate the final results of the thesis. A list of the parameters of interest can be seen in Table 4 further down in this section.

The output from the energy balance model has very high geographical and temporal resolution. To make it easier to get an overview of how climate change impacts the demand the results are grouped to present each parameter of interest on different levels of detail. The different levels of detail for the geographical resolution are the national level and two different kinds of regional levels. The national level gives an indication on how climate change will impact the national demand and the regional levels could show important regional aspects on the demand that would be missed if only looking at the national level. The reason for two different regional levels is since the SFD and MFD data are divided into four regions based on NUTS 2 division and the NRB data are divided into three different climate zones defined by the Swedish national board of housing [24]. The different climate zones will from now on be referred to as R1, R2 and R3 respectively and the counties included in the different regions can be seen in the list below [24]. Since the NRB are placed on three different geographical locations, as stated in Section 2.3, the different regions, R1, R2 and R3, represents the three locations Umeå, Sundsvall and Stockholm respectively.

- R1: Norrbottens, Västerbottens and Jämtlands county.
- R2: Västernorrlands, Gävleborgs, Dalarnas and Värmlands county.
- R3: Västra Götalands, Jönköpings, Kronbergs, Kalmar, Östergötlands, Södermanlands, Örebro, Västmanland, Stockholms, Uppsala, Skåne, Hallands, Blekinge and Gotlands county.

The different regions in the NUTS 2 division will be referred to as SE1, SE2, SE3 and SE4 as stated in Figure 3. This division is similar to the electricity price regions of Sweden, but not identical.

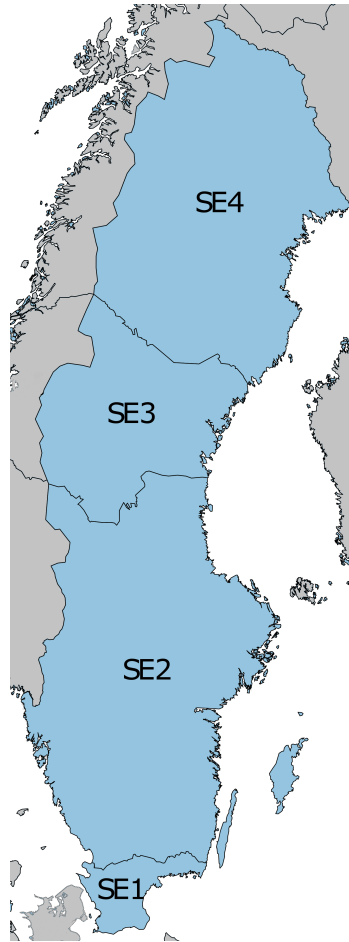


Figure 3: Map of the NUTS2 division, which are the different regions that the SFD and MFD are divided into when the regional calculations are done.

The results are either presented on a yearly- or seasonal basis. The seasonal division divides the result in a winter, spring, summer and fall group. The winter group is the result from the energy balance model that are dated in January to Mars, spring is April to June, summer is July to September and fall is October to December.

The different parameters of interest are the heating and cooling energy, the peak heating and cooling demand, the cooling energy and peak demand when cooling by open windows is subtracted and finally the heating period. A summary over the different parameters and the different levels of geographical and temporal detail can be seen in Table 4.

Table 4: List of the result parameters of interest and the different levels of geographical and temporal detail they are presented as.

Parameters	Geography	Time
Total heating demand	Nationally	Yearly Seasonally
	Regionally	Yearly Seasonally
Peak heat demand	Nationally	Yearly
		Seasonally
	Regionally	Yearly Seasonally
Total cooling demand	Nationally	Yearly Seasonally
	Regionally	Yearly Seasonally
Peak cooling demand	Nationally	Yearly Seasonally
	Regionally	Yearly Seasonally
Total cooling demand including window ventiation	Nationally	Yearly Seasonally
	Regionally	Yearly Seasonally
Peak cooling demand including window ventilation	Nationally	Yearly
		Seasonally
	Regionally	Yearly Seasonally
Heating period	Nationally	Yearly
Change in total demand in the different models	Nationally	Yearly
Change in peak demand in the different models	Nationally	Yearly

From the energy balance model the heating and cooling demand is calculated in kW at every time step, which is once every third hour. To get the demand of heating and cooling energy during all hours, kWh, every time step is multiplied by three to represent an average of the total amount of energy supplied during the whole three-hour period. The total

demand is then found by summarizing the heating and cooling respectively on the different geographical and temporal resolutions mentioned above and which can be seen in Table 4 above. For example, the heating energy is summarized over all buildings during one year to get the result stated first in Table 4.

Regarding the total cooling energy including ventilation through windows there is an extra step before summarizing the output. If the indoor air temperature at a specific time step is above the allowed temperature span and the outdoor air temperature is lower than the indoor air temperature, the cooling demand is subtracted by the cooling available through open windows. The remaining demand is what is needed to be sustained through a cooling system. If the cooling available by windows are larger than the actual cooling demand, the cooling needed to be sustained through a cooling system is set to zero. When this is done, the results are summarized in the same way as described in the section above.

The maximum effect is found by first summarizing the demand for all buildings at every specific time step to obtain the correct geographical resolution, either on national level or regional level. Then the hour within the specific time period, year or season, with the highest value is the peak demand within that specific time period. To investigate if the peak is due to an extreme or rare event four more values were investigated for the yearly case. The highest peak is the 100 % level, the second level is the 99% level where 1% of the highest peaks are disregarded and similar with the 98% and 97% levels. This gives an indication of how extreme the peaks that occurs are. If the change is similar for all levels, the pattern or variation will be similar for the different levels of global warming. If the change is different in the different levels, the pattern or variation of the highest 4% peak demand will change due to climate change.

The heating period is the period of time during a year when the heating systems are operating. The heating period ends in the beginning of the warmer months when there is no heating demand and starts again when it gets colder. The heating period is found by first summarizing the output from the energy balance model to get the yearly heating energy demand for all buildings. Starting from the middle of the summer period the hourly heating demand for all buildings are summarized, one hour at the time. When the summary of hourly heating demand reaches 2% of the yearly demand it marks the beginning of the heating period and when it reaches 98% it marks the end of the heating period. The reason for skipping the first and last 2% is since the real system will not start when the first kWh of heat demand exists. The first kWh of heat needed could be due to one extra cold summer night and is not something that will start the entire system. To test how this method of finding the heating period affects the result a limit of 1 and 3% are also tested and compared to the result from the 2% limit.

Change in total demand in the different models refers to a summary of how the different

models change in the total demand for the heating and cooling with and without cooling through windows. It shows the three climate scenarios 1.5°C - RCP 2.6, 1.5°C - RCP 8.5 and 2°C - RCP 8.5. The change is calculated by finding the average yearly demand in each model and climate scenario and then comparing it to the average demand of the specific model in the current scenario. The change in peak demand is calculated in the same way, the yearly average of the highest peak demand in the different models within each climate scenario is compared to the yearly average of the highest peak for the respective model in the current climate scenario.

3. Result

In this following section the results in the thesis are presented. First an introduction of the most common result figures will be given. After that the heating demand is presented. First the yearly and national result, then the regional and lastly the seasonal results are presented. In the next section the cooling demand is presented in the same order as the order as for the heating demand by starting with the national and yearly demand and finishing with seasonal changes. Next section is about the heating period and finally the different climate models are compared to each other.

3.1. Introduction to result figures and total yearly heating demand

This section introduces the most common result figures. A figure of the total yearly heating demand for the building stock is used for this, see Figure 4.

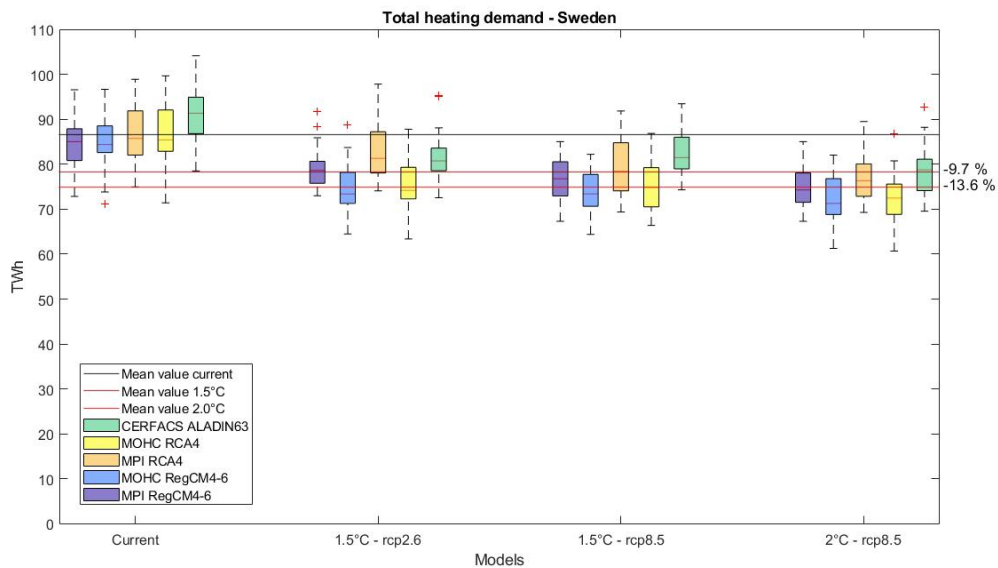


Figure 4: Total yearly heating demand in the Swedish building stock for the different climate scenarios and the different climate models. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

Every color on the boxes, purple, blue, orange, yellow and green, represent a climate model. Note that the purple and blue boxes have the same RCM, RegCM4-6, and the

orange and yellow boxes are the RCA4 RCM. The purple and the orange boxes have the same GCM, MOHC, and the lighter blue and yellow boxes are the MPI GCM. The green box has GCM CERFACS and RCM ALADIN63. Every box plot consists of a 30 year period as mentioned in previous chapters, meaning that the box plots in Figure 4 represents the yearly total heating demand for 20 different cases and 30-year periods. The small red horizontal lines in the center of every box plot marks the median of each scenario. The top and bottom of the box is the 25th and 75th percentiles and the dashed lines marks the rest of the data points without including the outliers, if a case has any outliers they are marked with a red cross, see the first blue box plot in Figure 4 as an example of an outlier. The black, light and dark red horizontal lines that span over the whole plot are the mean heating demand in each climate scenario, where black is current, dark red is 1.5°C and light red is 2°C global warming. To the left of the red lines there are numbers showing how much the average demand has changed compared to the current demand. The box plots are grouped in four categories on the x-axis, the different categories are the current, the 1.5°C for RCP 2.6, the 1.5°C for RCP 8.5 and the 2.0°C for RCP 8.5 category.

Most figures in the following section exists in two different versions, one with GWh or TWh on the y-axis and one with kWh/m²/ heated floor area on the y-axis. In some cases, both are present in the text and if not, both versions can be seen in Appendix A.

3.1.1. Total yearly heating demand

Looking at the results in Figure 4 the first thing to note is the overall demand change due to climate change. In the case of Figure 4 the current demand, the black line, is somewhere above 85 TWh per year in year 1985. Remembering Figure 1 in the Introduction, the real demand seems to have been somewhere between 90-100 TWh, including hot water demand, for the old building stock around 1985. The calculated average demand from the energy model is therefore quite close to the actual in 1985, however looking at the different box plots from the calculations there is quite a big span of variations between the different years. The highest is almost 105 TWh per year and the lowest is almost 70 TWh per year.

At 1.5°C global temperature increase, the dark red line, the demand has decreased by almost 10%, meaning a total yearly heating demand of short below 80 TWh. Remembering Table 2 from Section 2.2 this temperature increase happens around year 2018-2040 in the different models. Figure 1 from the Introduction ends at year 2018 with the demand being around 80 TWh, however that includes real and important changes to the building stock such as new buildings, renovations and so on. At 2°C global temperature increase, the red line, the demand has decreased almost 14% compared to the current level, which means a yearly total heating demand of 75 TWh.

Looking at the current climate scenario in Figure 4 again the different MPI and MOHC models are all within a close distance of each other, while the CERFACS model is slightly higher. Note that the models with the same RCM, the RCA and RegCM4-5 models respectively, are very similar in the current scenario. When 1.5°C is reached in the RCP 2.6 scenario the models with the same RCM is no longer as similar, but the ones with the same GCM seems to have decreased in similar ways, where GCM MPI did not decrease as much as GCM MOHC. The same can be seen in the other 1.5°C scenario and the 2°C scenario. Note that the comparison between 1.5°C and 2.0°C for RCP 8.5 have quite the bit of an overlap. This is since the years overlap in the different climate scenarios, see previous Table 2 in Section 2.2.

The model that changed the most in this case is the MOHC RCA4 climate model and the least is the MPI RCA4 model. In MPI RCA4 the total yearly demand decreased slightly above 10% for the 2°C temperature increase, while the MOHC RCA4 decreased 16%.

The differences between "1.5 - RCP 2.6" and "1.5°C - RCP 8.5" are not as distinct as between the other scenarios. The big changes in demand comes from a changed climate and not how fast the concentration in the atmosphere changes.

Figure 5 shows the yearly total heating demand per heated floor area. The Swedish Energy Agency states that the average heat demand per square meter is 116.2 kWh/m²//year. Comparing this with the results in Figure 5 it seems like the real current demand is pretty close to the 1.5°C mean demand. Even though the primary question of this thesis is to look at trends between the different scenarios it is interesting to see that the result that models the climate in the 2020s is close to the actual demand of 2018. The actual demand in year 1985 was 200 kWh/m²//year. This is a lot higher than for the modeled current case which is around 130 kWh/m²//year. This difference can be due to variations in the climate models or that the Swedish Energy Agency have data from the real building stock while these results are based on a newer building stock.

The only difference between Figure 5 and Figure 4 is the scaling of the results, kWh/m²/year and TWh/year. Meaning that the things regarding the changes stated about Figure 4 above applies to Figure 5.

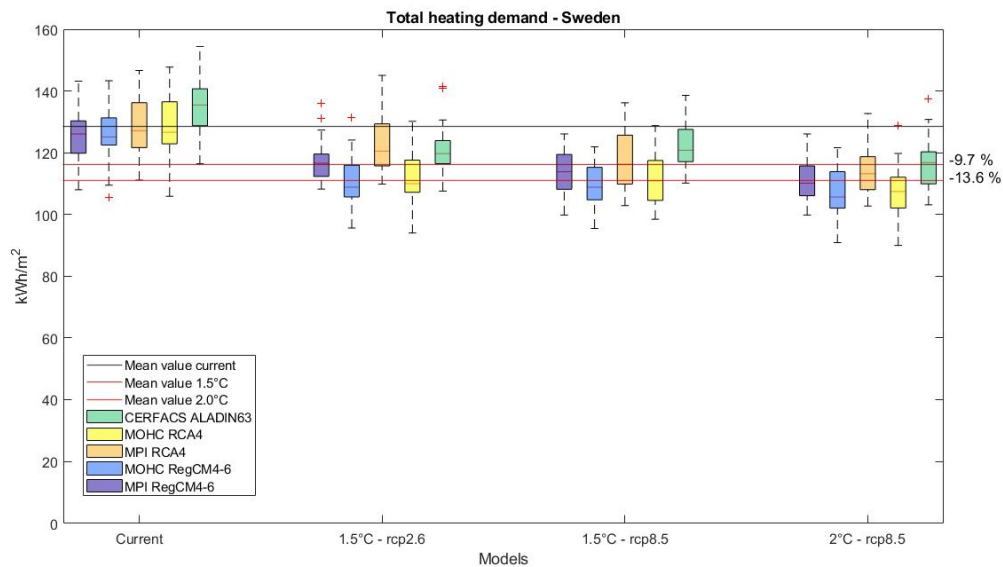


Figure 5: Total yearly heating demand in the Swedish building stock per heated floor area for the different climate scenarios and the different climate models. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

3.2. Heating demand in the building stock

In this section the heating demand is further investigated. Starting with the peak demand and after that investigating the regional aspects of the heating demand and ending this section with seasonal aspects.

3.2.1. Yearly peak heating demand

Figure 6 below shows the largest heating demand per hour during one year. The 1.5°C climate scenario has decreased 8.6% compared to the current climate scenario and the difference between the current scenario and the 2°C scenario is 10.5%. Remembering the change in total heating demand from the section above the total demand decreases more compared to the change in the highest peak demand. This could either mean that the future demand might vary more compared today while still having high peaks remaining, or that the winter or heating period is shorter, but it could still be cold periods during the winter time.

The different results in each scenario lay within a close range to each other, however there

is quite a big span within each scenario.

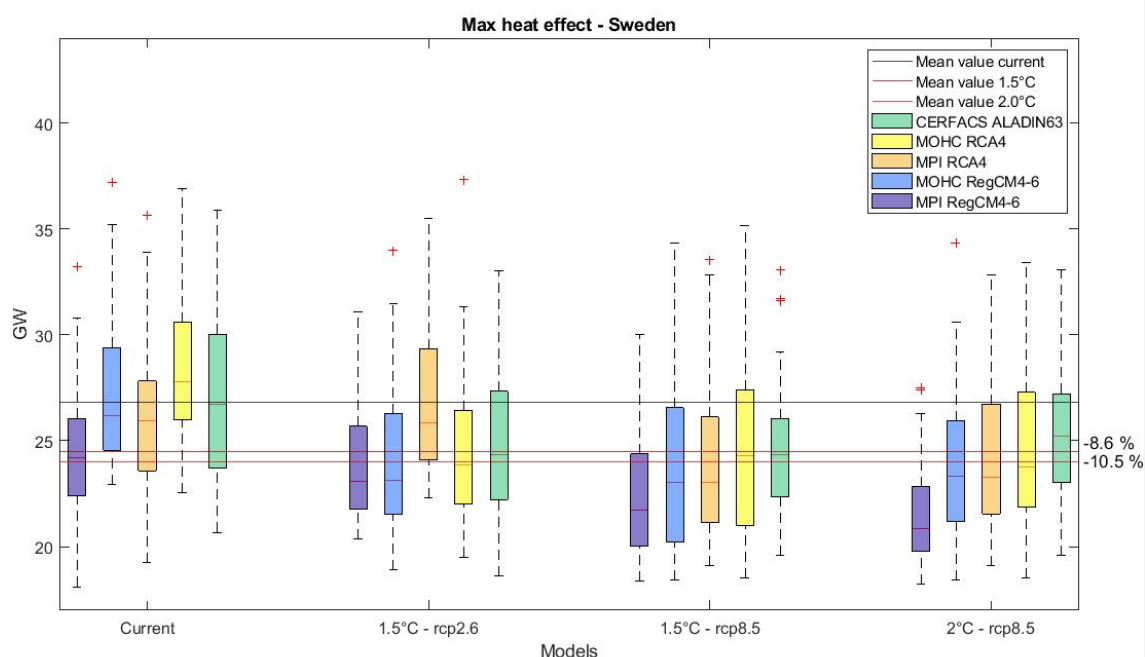


Figure 6: Yearly peak heating demand in Sweden for different models in the current, 1.5°C and 2°C climate scenarios. The black horizontal line marks the 30-year average of yearly peak demand in the current scenario, the dark red is the average in the 1.5°C scenario and the light red line is the peak demand in the 2°C scenario.

Figure 7 below describes the peak hours of the heating demand. The first square in the figure, marked with "100%", is the same figure as Figure 6 above. The other squares are the peak demand when shaving the 1%, 2%, 3% and 4% of the highest peaks respectively. Climate change seems to be affecting the peak demand the same way for all five different peak levels. The demand decrease at the 1.5°C climate scenario is around 6.6-6.9% and the demand decrease at 2°C temperature increase is around 10.6-10.8%. Based on this figure, the calculation of the different levels of peak demand seems to be affected by the climate change in the same way, meaning the variation between the highest 4% peaks will not be affected by climate change.

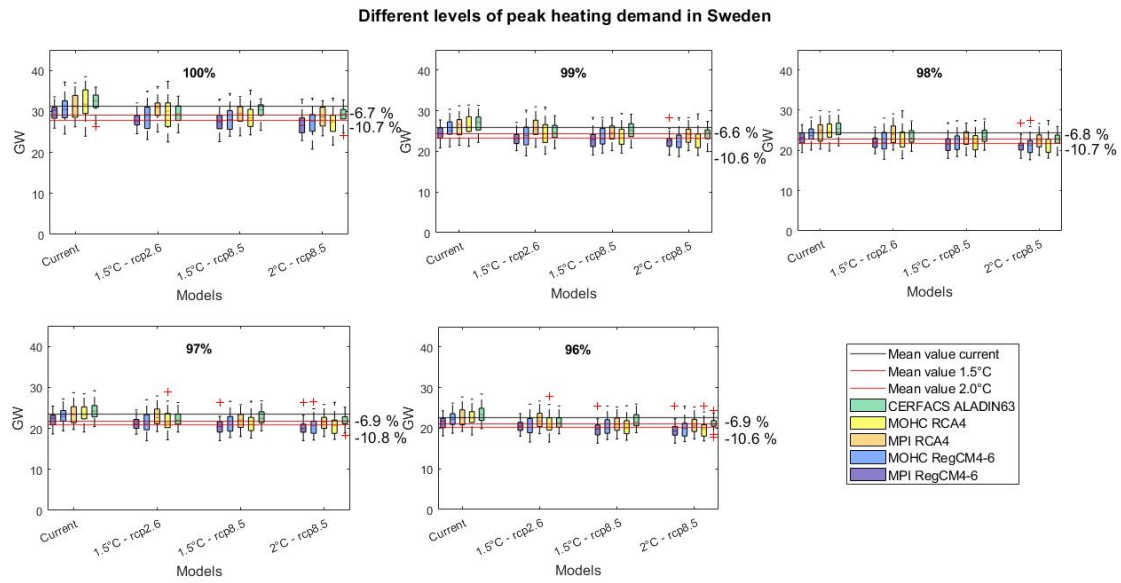


Figure 7: 4% of the yearly highest peak heating demand in Sweden. The different plots show how the climate is affecting 100%, 99%, 98% and 97% highest peak heating demand.

3.2.2. Yearly regional heating demand

In this section the regional changes will be investigated. Keep in mind when looking at the following result figures, that they only show a part of the building stock at the time. Either it is the result regarding the SFD and the MFD, or the result regarding the NRB. Therefore, the results in this section will somewhat differ from the result from section 3.1 above.

Figure 8 shows the yearly heating demand from SFD and MFD in region SE1, SE2, SE3 and SE4 per square meter. The demand changes due to climate impact is very similar in region SE1, SE3 and SE4, where the change decreases around 9.5% and 13.4%, for 1.5°C and 2°C climate scenario respectively. In region SE2 however, the change is somewhat smaller, around 8.8% and 12.3%.

Figure 8 also shows that the demand of heat is higher in the northern parts of Sweden where the climate is colder compared to the southern parts of Sweden.

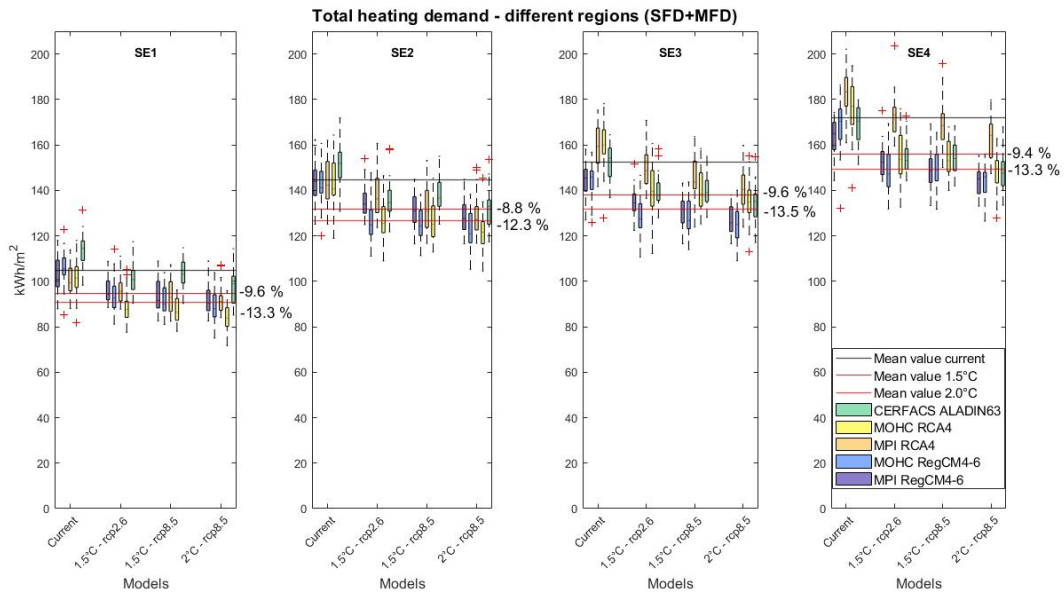


Figure 8: Total yearly heating demand per square meter in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

Figure 9 shows the yearly heating demand in the different regions SE1, SE2, SE3 and SE4. Note that the trend is the same in this figure as in Figure 8 above. The only difference between them is that Figure 8 shows the heating demand per area unit and Figure 9 the total heating demand per region. In Figure 9 it is clear that the heating demand is much higher in region SE2 compared to the other regions. The reason for this is since SE2 is the region where most of the Swedish buildings are located.

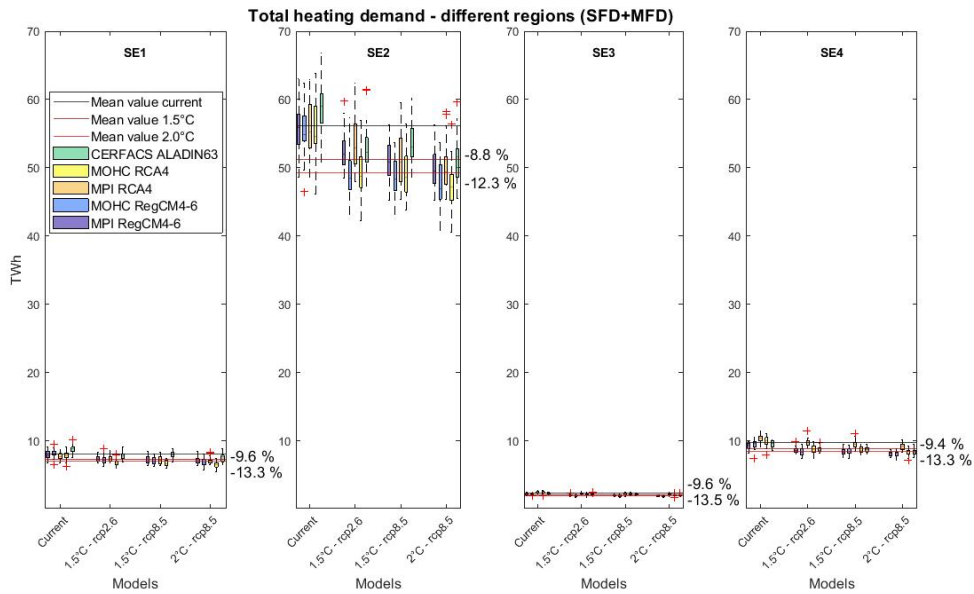


Figure 9: Total yearly heating demand in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

In Figure 10 the heating demand for the climate zones R1, R2 and R3 can be seen. These climate zones only include the NRB. Compared to the current level, the demand changes between 14.4-15% at 1.5°C average global temperature increase and 20.2-20.9% at 2°C average global temperature increase. These numbers are much higher than the national values, see Section 3.1. The NRB are placed on three different geographical positions, one position in each climate zone, as mentioned in Section 2.3. This could be the reason for the changes to be bigger in this case compared to the national result. This implies that the impact due to climate changes varies with geographical resolution and that more regional studies of the demand changes could be important.

One other difference between this result and the previous is that there are larger variations between the different models compared to before. The reason for this could also be due to only plotting the result from one geographical location. It appears like the different models are better at showing the same result when a larger geographical area is investigated and when looking at only one coordinate or data node they differ more.

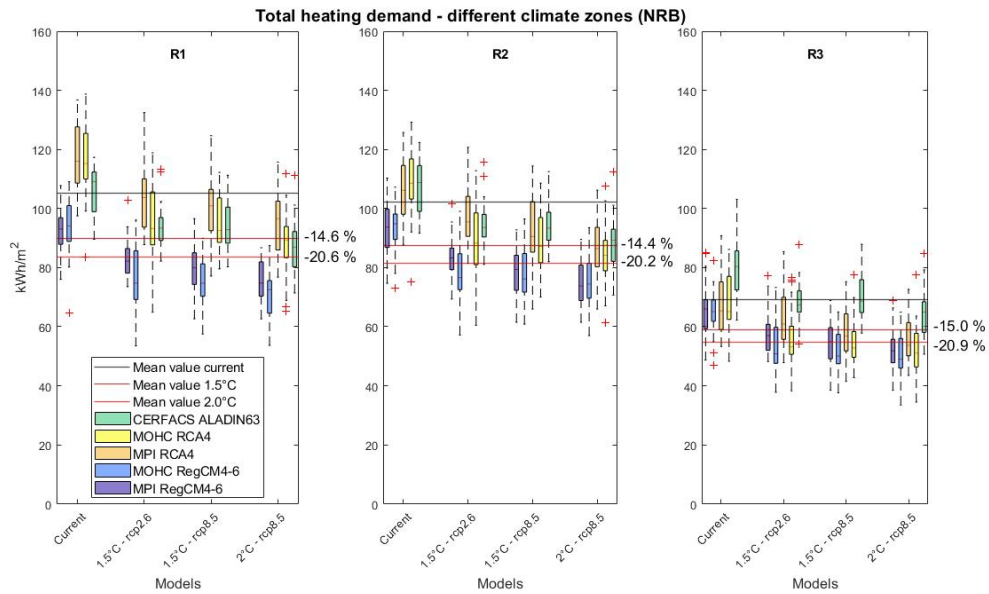


Figure 10: Total yearly heating demand per area unit in the different regions, R1, R2 and R3, only including NRB. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

3.2.3. Yearly peak heating demand per region

In this section the yearly peak heating demand per region is investigated. Figure 11 shows the peak demand in regions SE1, SE2, SE3 and SE4 for the SFD and MFD. Here the biggest change seems to happen in SE3 where the demand decreases 6.7% and 10.8% in climate scenario 1.5°C and 2°C respectively. The smallest change is in region SE4 where the change is 5.1% and 8.3%, which is not very far from the maximum regional change in SE3. However, the variation between the different climate models seems to be the biggest in SE4, while in the other regions, SE1, SE2 and SE3, the climate models are within a closer range. The highest peak demand is seen in the northern parts of Sweden, SE4, and the smallest peak in southern Sweden, SE1.

When comparing the change in total heat and the change in peak demand in Figures 4 and 6 it showed that the total heating demand decreased more than the peak. The same thing can be seen in the regional cases when comparing Figures 9 and 11. There is less change in peak demand than in total yearly demand for all regions.

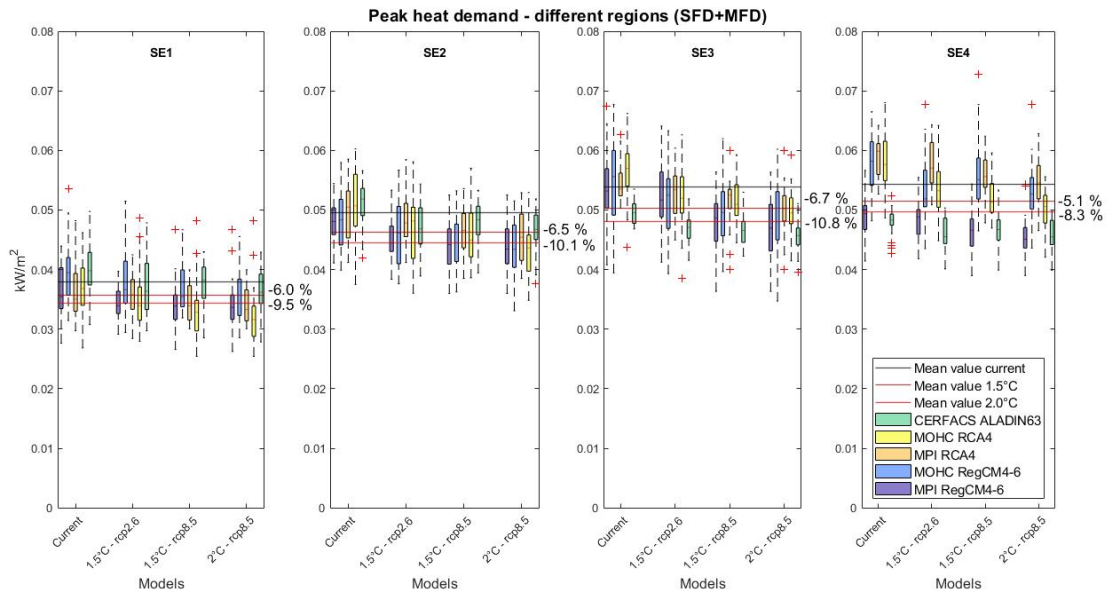


Figure 11: The yearly peak heating demand in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD. The black horizontal line marks the 30-year average of yearly peak demand in the current scenario, the dark red is the average in the 1.5°C scenario and the light red line is the peak demand in the 2°C scenario.

Figure 12 shows the peak heating demand in regions R1, R2 and R3 for the NRB. The largest change is in region R2 where the peak demand changes 7.8% and 12.6% for the 1.5°C and 2°C climate scenario. The least change can be seen in R3 which is changed by 6.8% and 11.4% for 1.5°C and 2°C respectively. Just as for the SFD and MFD the northern part of Sweden, R1, shows more variations between the different climate models than the southern parts.

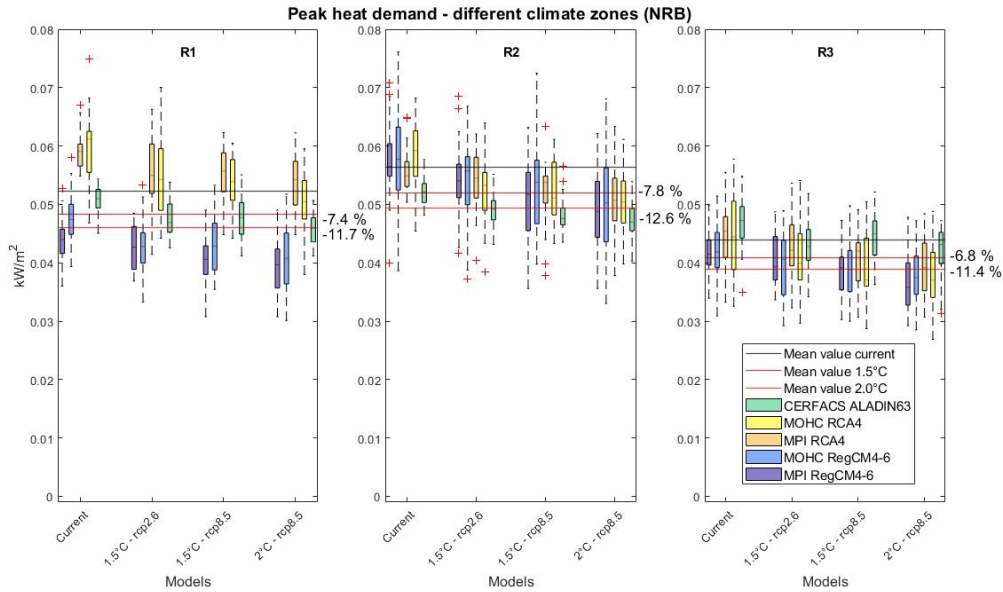


Figure 12: The yearly peak heating demand per area unit in the different regions, R1, R2 and R3, only including NRB. The black horizontal line marks the 30-year average of yearly peak demand in the current scenario, the dark red is the average in the 1.5°C scenario and the light red line is the peak demand in the 2°C scenario.

3.2.4. Seasonal changes to the heating demand

Figure 13 illustrates the demand of heat during different seasons. The winter season is as previously mentioned defined as December to February, spring is March to May, summer is June to August and fall is September to November. The figure shows the relative change during the different seasons. The winter demand changes by 6.5% and 9.8% at 1.5°C and 2°C temperature increase respectively. Climate change affects the fall demand by 12.9% and 16.8%, the spring demand 9.7% and 13.8%, and finally the summer demand by 19.3% and 26% for the 1.5°C and the 2°C scenario respectively. The reason for the change in summer demand being larger than the winter demand is since the summer demand is low to begin with. As seen in Figure 13 the summer demand is decreased around 2 TWh, while the winter demand is decreased around 8 TWh.

In the 1.5°C climate scenario the average yearly demand decreased by 9.7% and 13.6% in the 2°C climate scenario, remember Figure 4. When combining the results from Figure 4 with the results in Figure 13 it is possible to identify when the yearly change occur. In the 1.5°C scenario the biggest change occurs in the fall and winter season where 31.6% and 29.5% of the yearly change take place. In the summer season 13.55% of the yearly

change happens, this is the season where the least change occurs. 25.34% of the yearly change happens in the spring season. The 2°C climate scenario is similar to the 1.5°C scenario. The largest demand change is during fall and winter, 29.37% and 31.94% and the least change occurs during the summer season, 13.03%. 25.66% of the yearly change occurs in the spring season. These results correlates well with what SMHI states about global warming heating winter time average temperature more than summer time average temperature in Sweden [25].

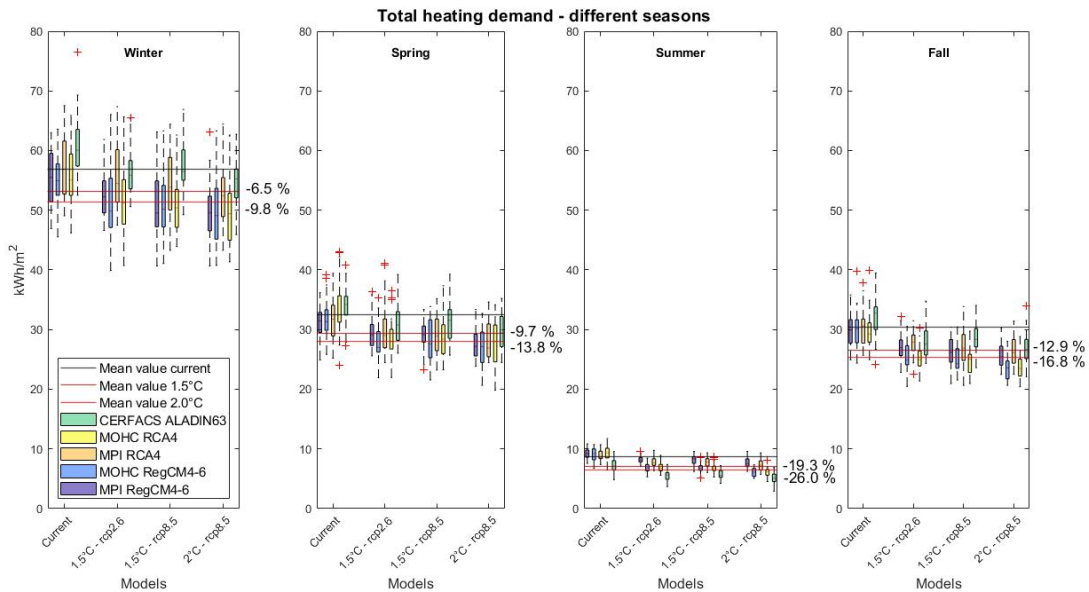


Figure 13: Total heating demand during different seasons for the current, 1.5°C – RCP 2.6, 1.5°C – RCP 8.5 and 2°C – RCP 8.5 climate scenarios. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

Figure 14 shows how the peak demand changes during the winter, spring, summer and fall seasons. The peak during the winter season decreases by 6.5% and 10.4% during the 1.5°C and 2°C scenario. In the 2°C scenario the peak changes more than the actual demand. This is the only case where the peak changes more than the actual demand. The spring peak changes 7.2% and 10.2% for the 1.5°C and 2°C scenario, the summer changes 12.2% and 16.7% and the fall season changes 8.9% and 11.7% for the 1.5°C and 2°C scenario.

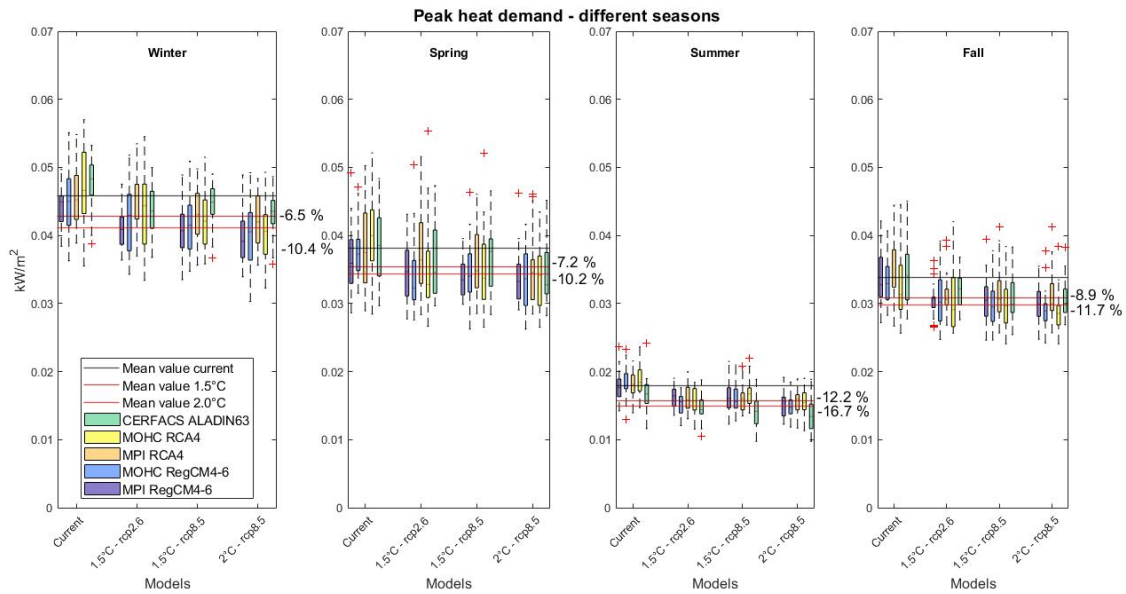


Figure 14: Peak heating demand during different seasons for the current, 1.5°C – RCP 2.6, 1.5°C – RCP 8.5 and 2°C – RCP 8.5 climate scenarios. The black horizontal line marks the 30-year average of yearly seasonal peak demand in the current scenario, the dark red is the average in the 1.5°C scenario and the light red line is the peak demand in the 2°C scenario.

3.3. Cooling demand in the building stock

The following section describes the cooling demand. First the total yearly cooling demand is presented, then the yearly peak cooling demand. After that the regional cooling demand and peak demand is presented. Finally, the seasonal demand of cooling and peak demand is presented.

3.3.1. Total yearly cooling demand

Figure 15 shows the total yearly cooling demand. The yearly cooling demand increases with 21.1% between the current and 1.5°C scenario and 27.6% between current and 2°C climate scenario.

Compared to the heating demand, there are more variations between the different models. However, the statements made regarding how the GCM and RCM affects the change seems to apply to the cooling demand in a similar way as for the heating demand, remember Figure 4. The models with the same RCM seems to be at the same level, while the GCM

affects how much they change. Looking at the RegCM4-6 models, the blue and purple box plots, they are relatively close to each other and the RCA4 models, the yellow and orange box plots, are lower compared to RegCM4-6 and on a similar level to each other. The MPI models, the purple and the orange box plots, are less affected by climate change than the MOHC models, the blue and yellow box plots, are. This was the case for the total heating demand as well, see Figure 4. The conclusion can be made that the GCM decides the trend between the different scenarios and the RCM decides the magnitude of the demand.

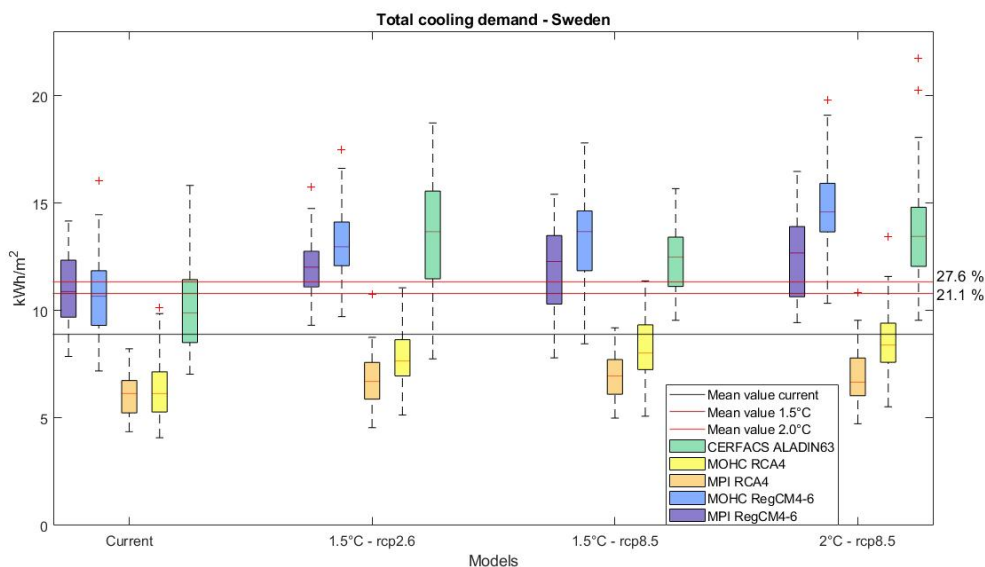


Figure 15: Total yearly cooling demand per m² for the current, 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

Figure 16 shows the total yearly cooling demand when including cooling through windows. When comparing Figure 15 and 16 it is clear that the current cooling demand is around 20% lower in the case where cooling through windows is available compared to the case where it is not available. The changes in demand are however larger in the case with cooling through windows. For the 1.5°C scenario the yearly cooling demand is increased 26.5% and for 2.0°C global warming the cooling demand increases with 34.7%. The reason for the change being larger in the case with window cooling could be since the opening of windows prevents from implementing a cooling system in the current case, but when the global temperature increases the outdoor air will not be able to provide as much cooling as before.

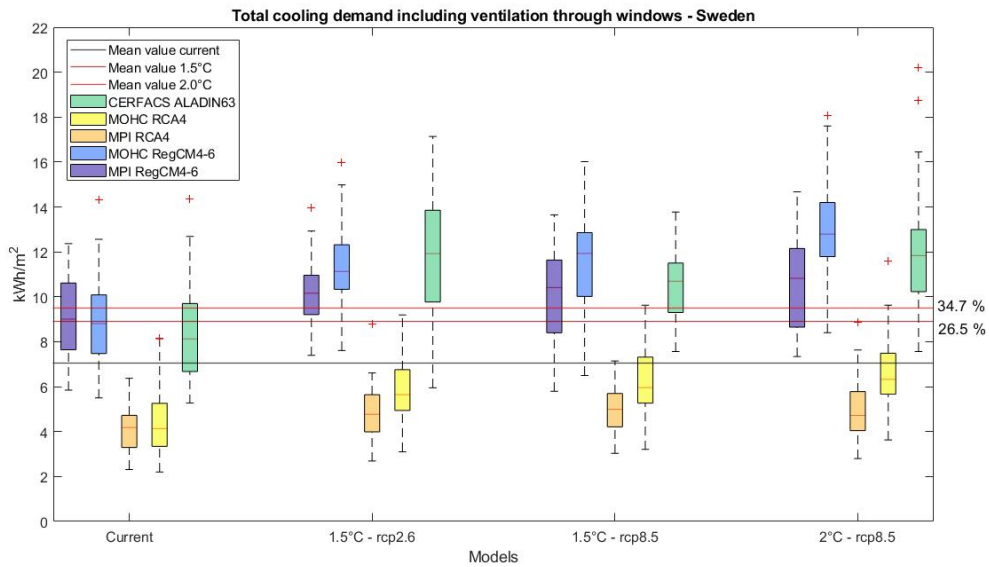


Figure 16: Total yearly cooling demand per m² including cooling through windows for the current, 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

3.3.2. Yearly peak cooling demand

Figure 17 shows the yearly peak cooling demand. The peak cooling demand increases 7.6% in scenario 1.5°C and 8.4% in scenario 2°C compared to the current scenario. Compared to the change in total cooling demand, this is a much smaller change.

In Figure 17 there are a few outliers that exist above the different box plots. This indicated that there are a few years with extremely warm summers.

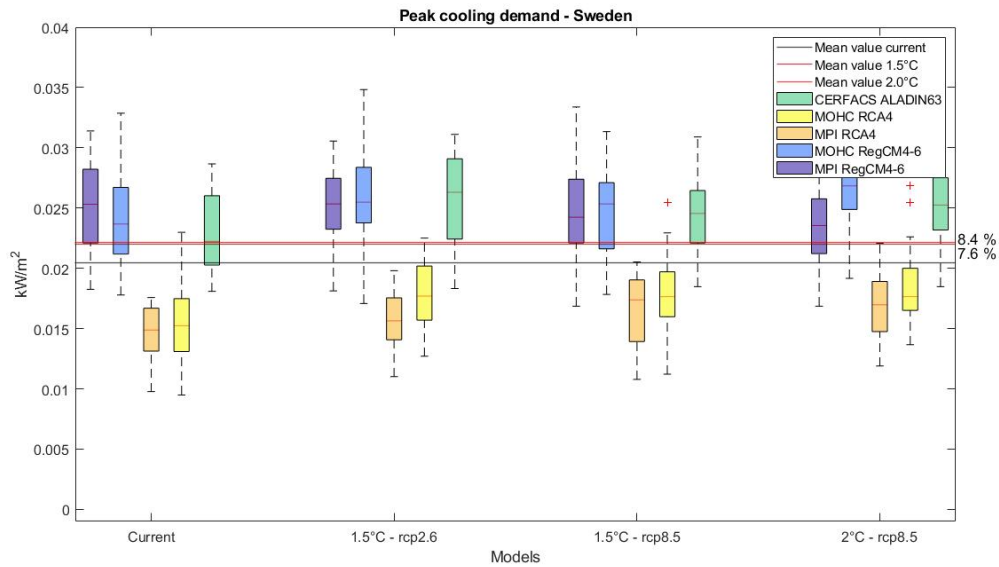


Figure 17: Yearly peak cooling demand per m² without cooling through windows for the current, 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. The black horizontal line marks the 30-year average of yearly peak demand in the current scenario, the dark red is the average in the 1.5°C scenario and the light red line is the peak demand in the 2°C scenario.

Figure 18 shows the yearly peak cooling demand when including ventilation through open windows. The yearly peak cooling demand increases 8% in scenario 1.5°C and 8.9% in scenario 2°C compared to the current scenario. Similar to the difference between Figure 15 and 16 the result that includes the option of ventilation through windows shows a higher increase in demand due to climate change, but the actual peak demand is lower in this case.

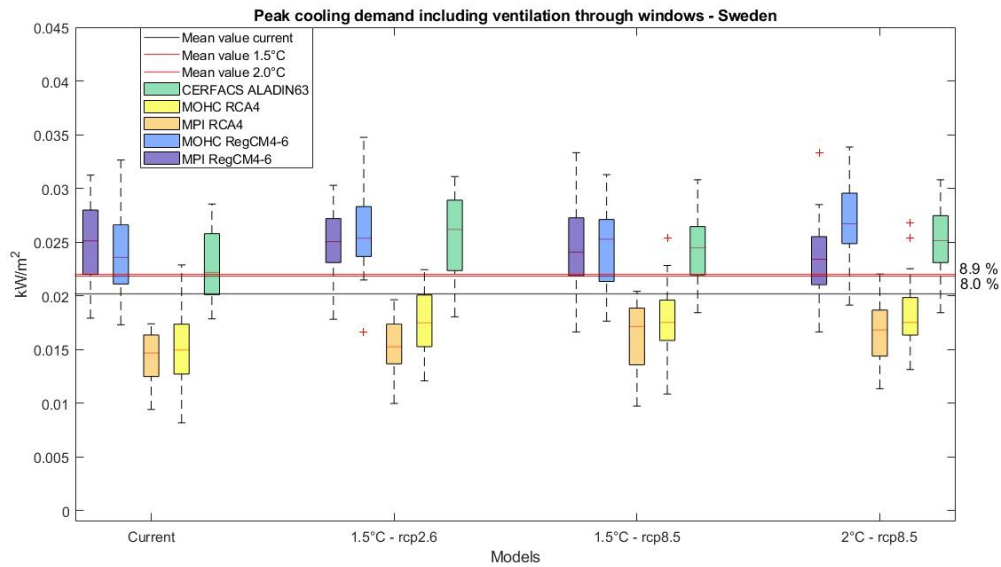


Figure 18: Yearly peak cooling demand per m^2 including ventilation through windows for the current, 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario. The black horizontal line marks the 30-year average of yearly peak demand in the current scenario, the dark red is the average in the 1.5°C scenario and the light red line is the peak demand in the 2°C scenario.

Figure 19 describes the hours of peak cooling demand. The first plot is the highest peak and the other plots are the peaks when shaving of the 1%, 2%, 3% and 4% of the highest peak cooling demand. The 100% highest peak increases 6.9% and 8.4% for the 1.5°C and 2°C scenario and the 96% highest peak increases 15.9% and 22.1%. The lower peaks appear to increase more than the higher peaks. This gives the indication that variation between the peak cooling demand hours might decrease if the global average temperature increase.

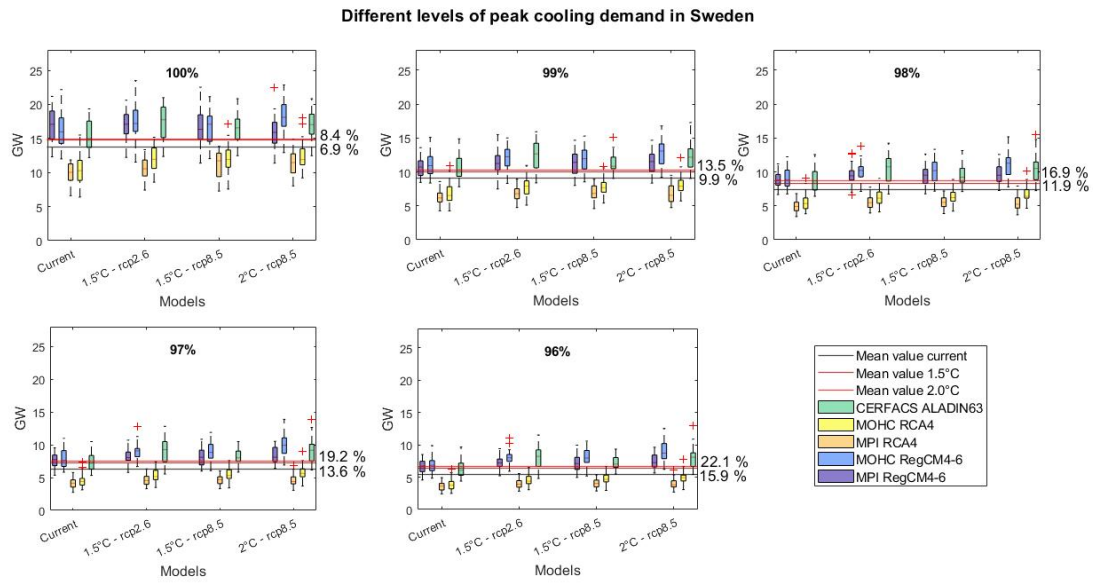


Figure 19: 4% of the yearly highest peak cooling demand in Sweden. The different plots show how the climate is affecting 100%, 99%, 98% and 97% highest peak cooling demand for the 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario.

Figure 20 is similar to Figure 19, but it includes cooling through windows. The overall changes are bigger in this case with 7.2% and 8.9% for climate scenario 1.5°C and 2°C in the 100% case. This is the smallest increase of all the different levels of peak demand. The 96% plot shows the largest change which is 20.9% and 28.9% for the 1.5°C and 2°C climate scenario.

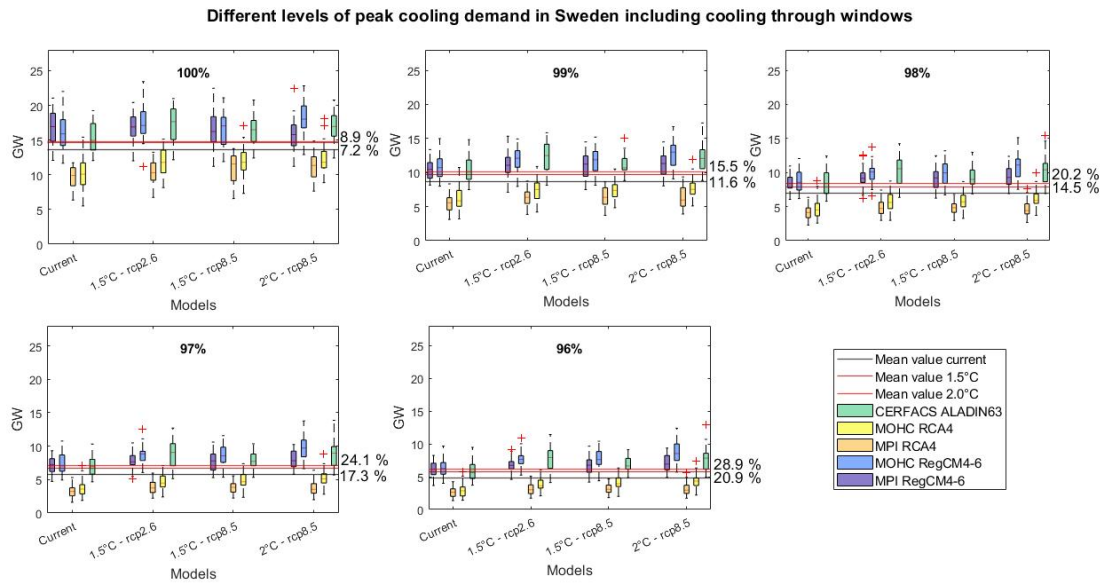


Figure 20: 4% of the yearly highest peak cooling demand in Sweden when including ventilation through windows. The different plots show how the climate is affecting 100%, 99%, 98% and 97% highest peak cooling demand for the 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario.

3.3.3. Yearly regional cooling demand

Figure 21 shows the yearly cooling demand and the relative change in demand due to climate change for the different regions SE1, SE2, SE3 and SE4. Note that this figure only applies to SFD and MFD and not to the entire building stock. The largest change can be seen in region SE4, which is the northern part of Sweden where the cooling demand changes 29.5% at scenario 1.5°C and 39.9% at scenario 2°C. The smallest change is seen in region SE1, which is the southern part of Sweden. In SE1 the cooling demand increases 16.4% and 20.3% for scenario 1.5°C and 2°C respectively. The variations between the different models seems to be the same between the different regions, where the RegCM4-6 and ALADIN63 models are higher than the RCA4 models.

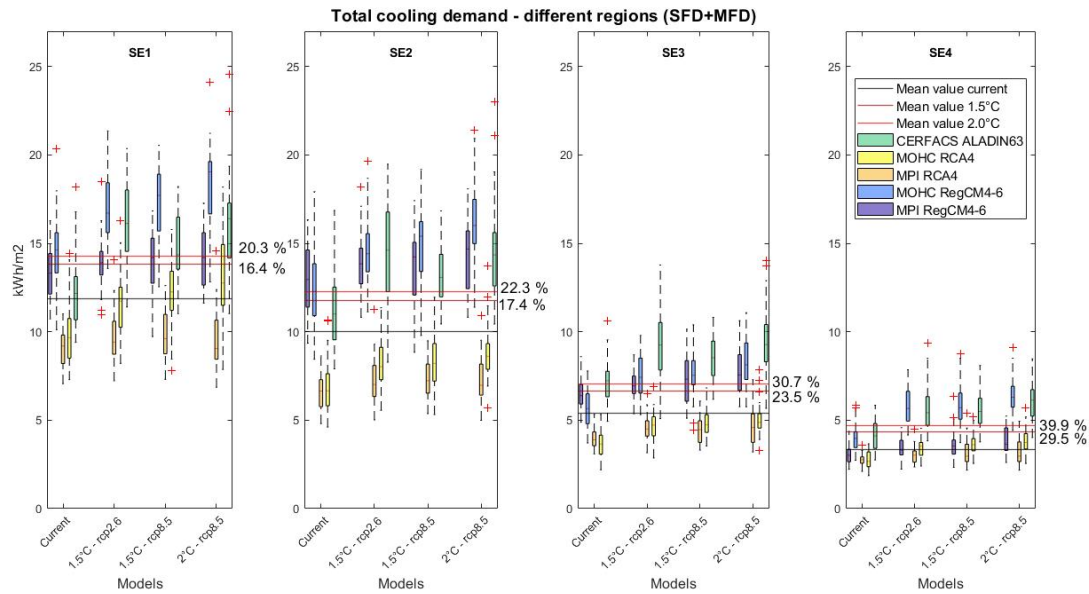


Figure 21: Total yearly cooling demand per area unit for regions SE1, SE2, SE3 and SE4. Excluding ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

Figure 22 is the same as Figure 21 above, but it includes cooling by open windows. Compared to Figure 21, Figure 22 shows a bigger change between the different scenarios. The largest change is seen in region SE4 and the smallest in SE1, just as above. The demand change in SE4 is 51.9% and 70.7% for the 1.5°C and 2°C scenario and in SE1 it is 21.8% and 27.4% for the 1.5°C and 2°C climate scenario. The variations between the different climate models is similar in the cases with and without cooling through windows.

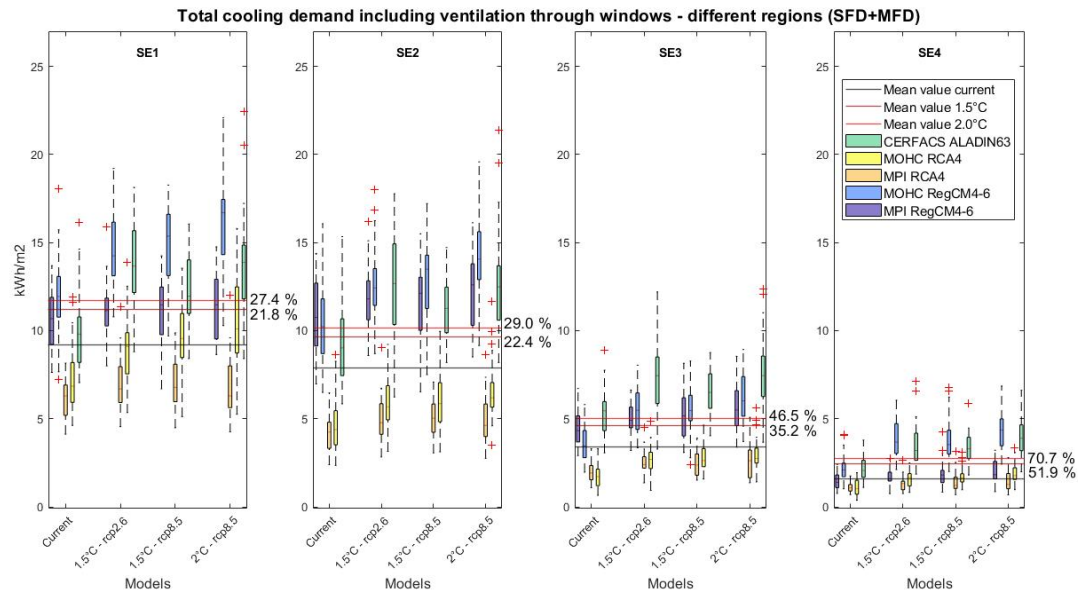


Figure 22: Total yearly cooling demand per area unit for regions SE1, SE2, SE3 and SE4. Including ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

In Figure 23 below the yearly cooling demand for the regions R1, R2 and R3 can be seen. This figure only includes results regarding the NRB. The largest change is in region R1, the northern region, where the cooling demand is increased 48.1% in the 1.5°C scenario and 66.6% in the 2°C scenario. The least change is in region R2 where the demand change with 34.6% and 48.4% in the different scenarios.

Other than the changes in demand, region R1 stands out from the other three regions and the regions regarding the SFD and MFD, see Figures 21 and 22. In region R1 the RegCM4-6 models are the models with the least demand of cooling. This is the only case where this happens. Since R1, R2 and R3 only consists of one geographical location each the reason for the RegCM4-6 being low in R1 can be due to a cold node at that specific geographical location in the RegCM4-6 climate model.

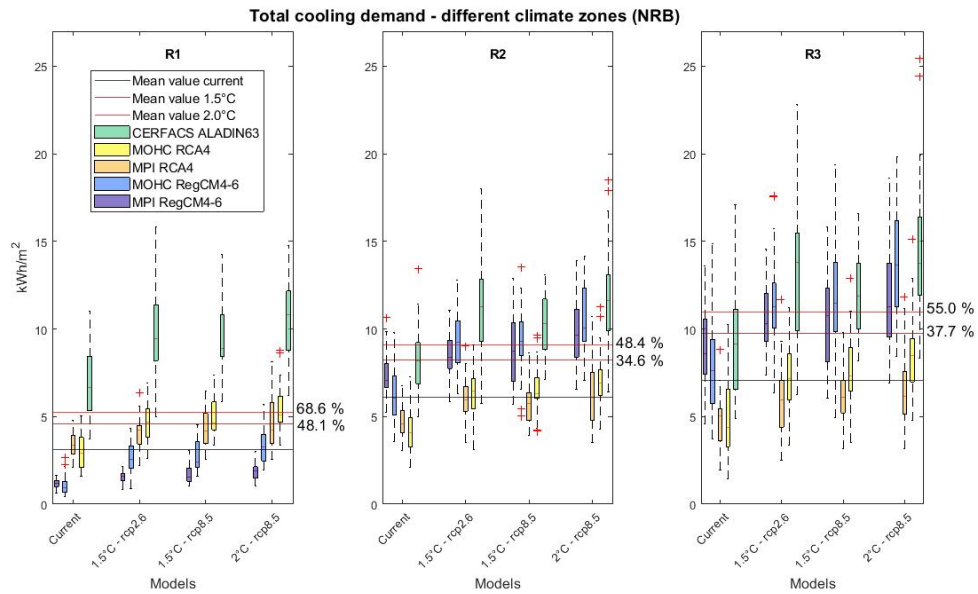


Figure 23: Total yearly cooling demand per area unit for regions R1, R2 and R3. Excluding ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

Figure 22 shows the cooling demand for the regions R1, R2 and R3, which only includes the NRB, when cooling through open windows is possible. Compared to Figure 21, the changes in Figure 22 are much larger, but the variation between the models seems to be the same, just as in the other cases. The largest change is seen in R1 where the cooling demand is changed 54.5% and 79.2% in the 1.5°C and 2°C climate scenario. The least change is seen in region R2 where the demand changes 38.1% and 53.6% for the respective climate scenario.

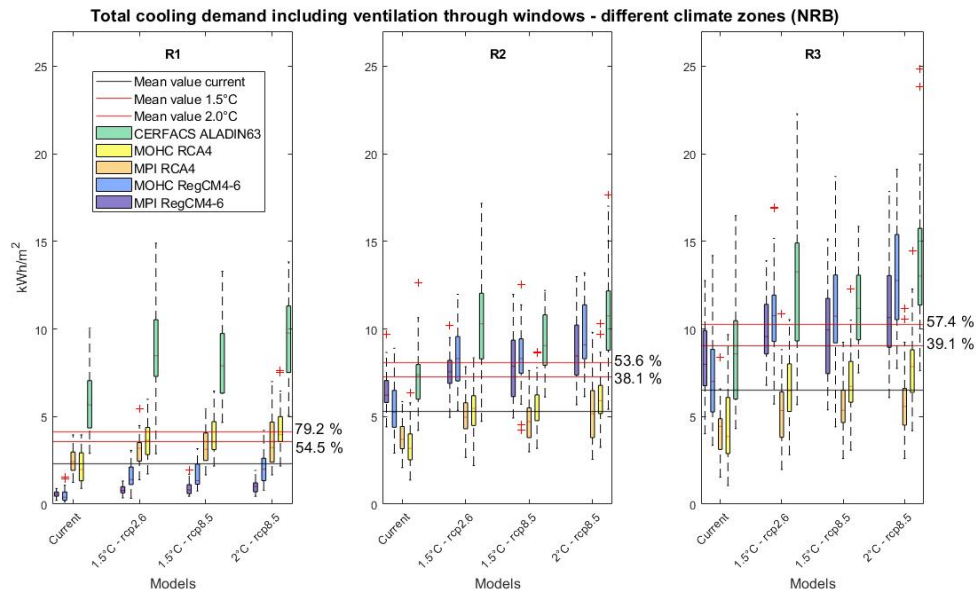


Figure 24: Total cooling demand per area unit for regions R1, R2 and R3. Including ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

3.3.4. Yearly maximum cooling effect per region

Figure 25 shows the peak yearly demand in regions SE1, SE2, SE3 and SE4, which only includes the results from SFD and MFD. The change in peak demand is highest in northern Sweden in region SE4 where the demand increases 13.8% in climate scenario 1.5°C and 18% in climate scenario 2°C. The least change is seen in region SE1 where the demand changes 10.9% in scenario 1.5°C and 13.6% in scenario 2°C.

When comparing the result from the regional peak demand with the regional total demand, see Figure 25 and 21, the impact of climate change is bigger in the case with total cooling demand. The same thing has been stated for all cases comparing change in total demand with change in peak demand.

One other thing to note in Figure 25 is that there are a lot of outliers above the box plots. This gives the indication that there will be some extremely hot summers within the different climate scenarios. For instance, if looking at the CERFACS model in SE2 for the "1.5°C - rcp2.5" - scenario the largest peak year is around 0.034 kW/m² and the smallest peak year is around 0.012 kW/m². This means that the largest peak year is 280% larger than the lowest peak year. This is a very large variation.

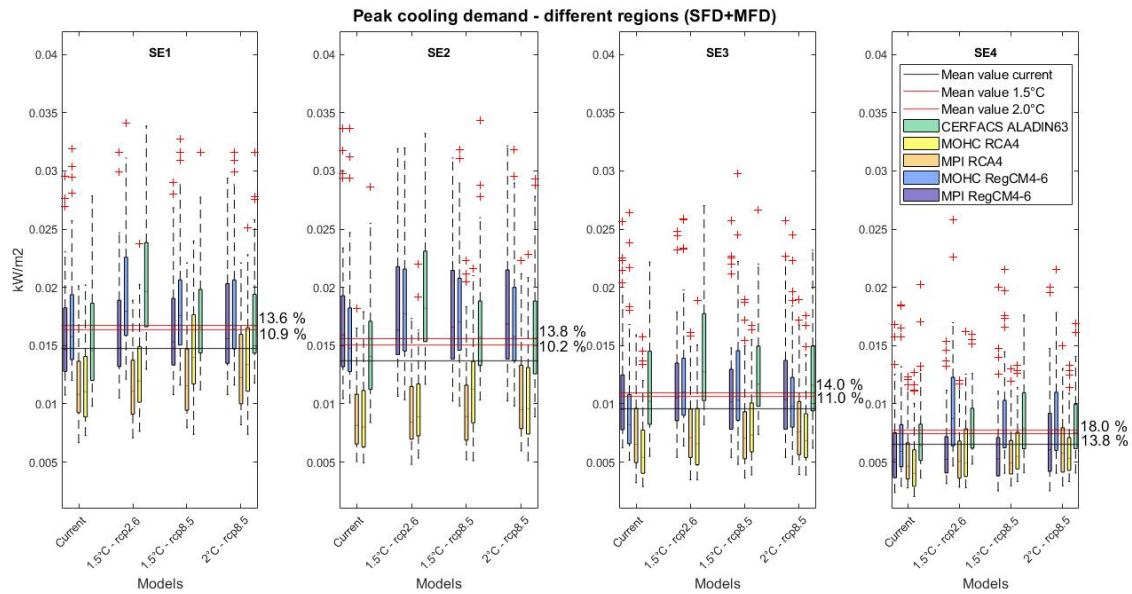


Figure 25: Yearly peak cooling demand per area unit for regions SE1, SE2, SE3 and SE4. Excluding ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

Figure 26 shows the peak yearly cooling in regions SE1, SE2, SE3 and SE4. The figure only includes results from SFD and MFD. These results look as expected, with the results being larger than the case without ventilation through windows and with the change between the different climate scenarios being smaller than in Figure 22. The largest change in Figure 26 is in region SE4 with the change being 24.6% in scenario 1.5°C and 31.6% in scenario 2°C.

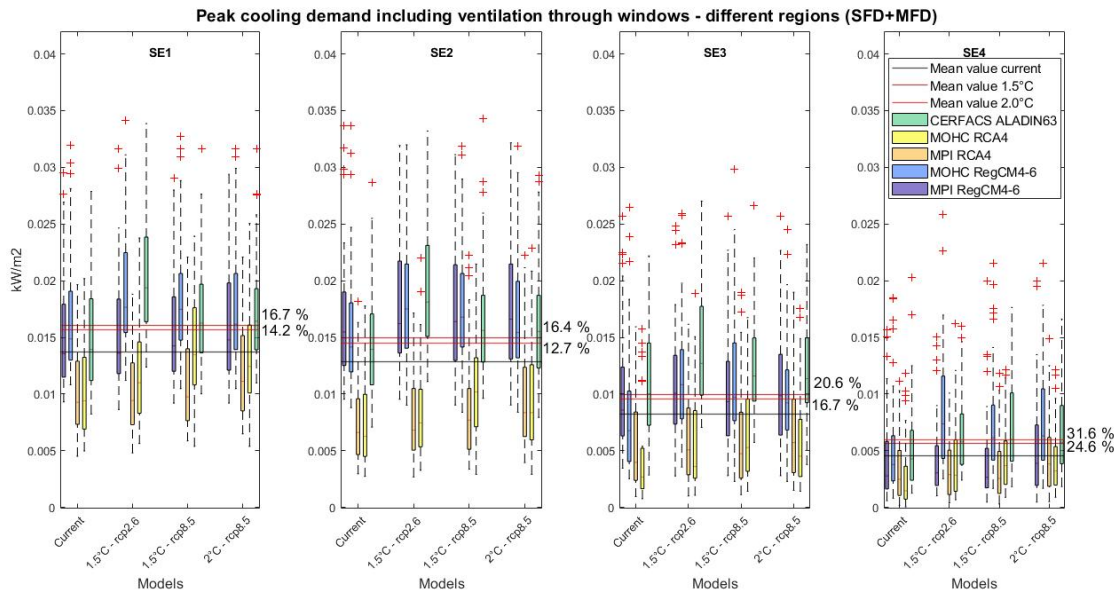


Figure 26: Yearly peak cooling demand per area unit for regions SE1, SE2, SE3 and SE4. Including ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

Figure 27 shows the yearly peak cooling demand in regions R1, R2 and R3. Note that this figure only includes the NRB. The largest change occurs in region R1, just as expected. The peak demand changes with 15.4% and 20.7% for scenario 1.5°C and 2°C respectively. The smallest change is in region R3, where the peak demand increases 7.6% and 9.1% in scenario 1.5°C and 2°C respectively.

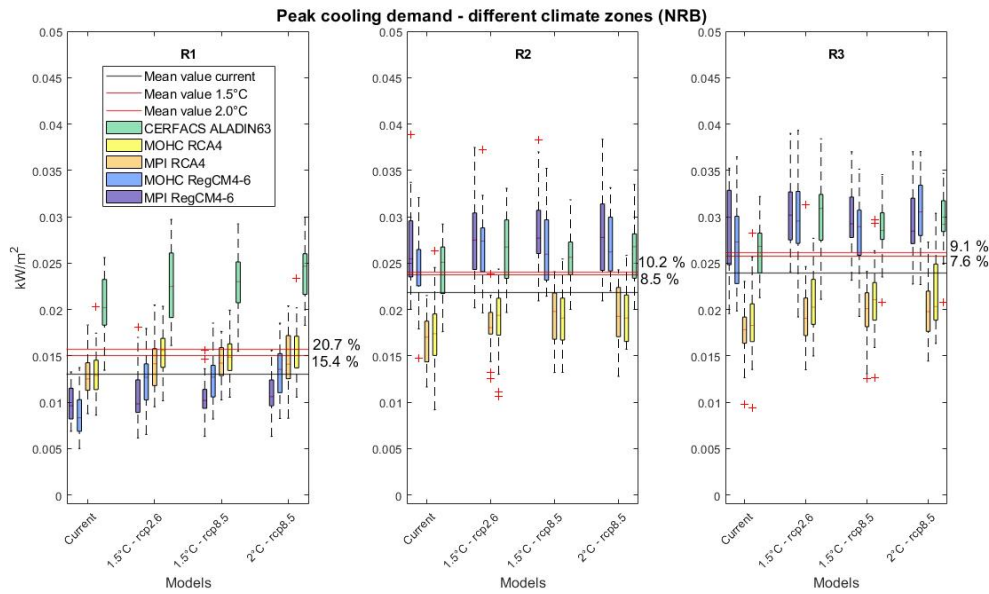


Figure 27: Yearly peak cooling demand per area unit for regions R1, R2 and R3. Excluding ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

Figure 28 show the peak cooling demand in the different regions R1, R2 and R3 when including ventilation through windows. The results in this figure are very similar to the results in Figure 27, the only difference is seen in region R1, where the peak demand is increased slightly more in the case with cooling available through windows. The cooling increases 15.7% and 21.1% in climate scenario 1.5°C and 2°C.

The reason for the results in Figures 27 and 28 being similar can come from the fact that only NRB are included. NRB are often larger buildings which suggests that they can keep a low indoor temperature for a longer period of time. The times when the building needs cooling the outdoor air temperature might be too high to be able to provide any cooling through open windows.

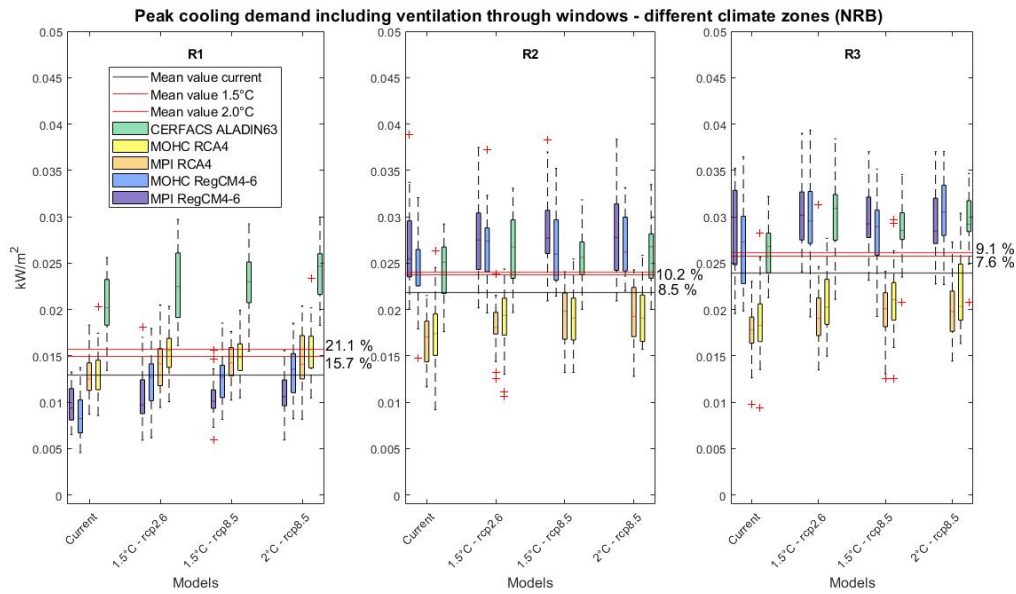


Figure 28: Yearly peak cooling demand per area unit for regions R1, R2 and R3. Including ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

3.3.5. Seasonal changes to the cooling demand

Figure 29 and 30 shows the cooling demand and how it is influenced by climate change during the different seasons. Figure 29 does not include ventilation through windows, while Figure 30 does. The figures show the relative change during the different seasons.

In Figure 29 the winter demand changes with 94.3% and 484.1% in climate scenario 1.5°C and 2°C. The cause of the large change is since the figure shows the relative change in each season. The spring demand changes 18.9% and 29%, summer changes 20.5% and 26.2% and fall changes 34.7% and 41.4% in the 1.5°C and 2°C climate scenario.

When looking at how the demand changes per season in relation to the yearly demand change it is clear that the greatest change occurs during the summer time. 74.7% and 73.61% in scenario 1.5°C and 2°C respectively of the total change in cooling demand occurs during the summer season. The second largest change is during the spring season where 16.34% and 17.27% in climate scenario 1.5°C and 2°C respectively happens. The least change occurs during the winter time where the cooling demand is increased by 1.2% and 0.29% in climate scenario 1.5°C and 2°C.

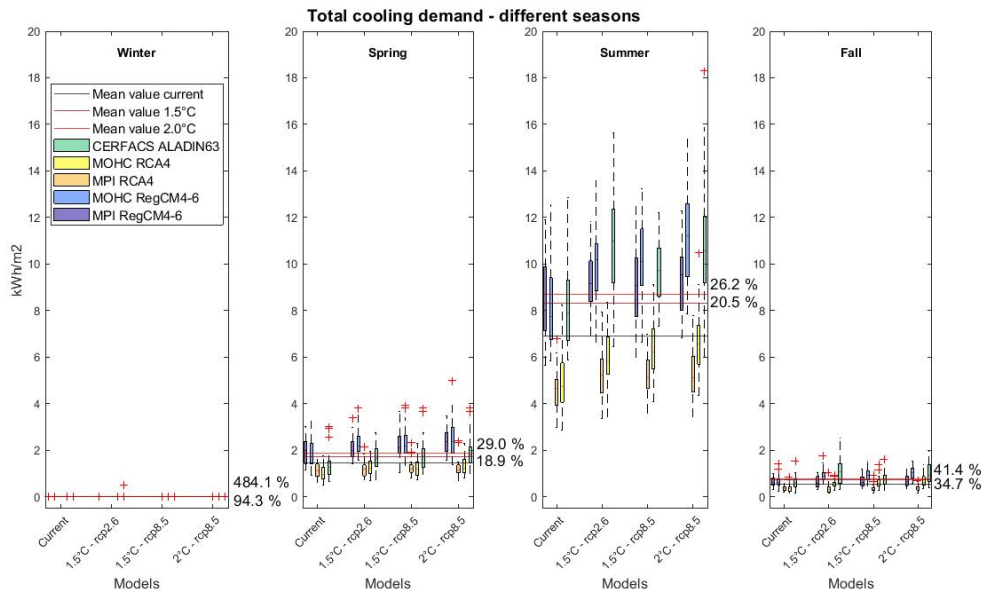


Figure 29: Total cooling demand during different seasons per area unit excluding ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

The results in Figure 30 are similar to the results in Figure 29, but the change in cooling demand is greater in the case where cooling through windows is allowed except during winter in climate scenario 1.5°C where the relative change in cooling demand is 43.7%. The amount of cooling needed is on the other hand less in the case where ventilation through windows are possible.

When comparing this to the yearly cooling demand a slightly higher share of that change occur in the summer season. 78.86% and 77.54% increase in scenario 1.5°C and 2°C respectively.

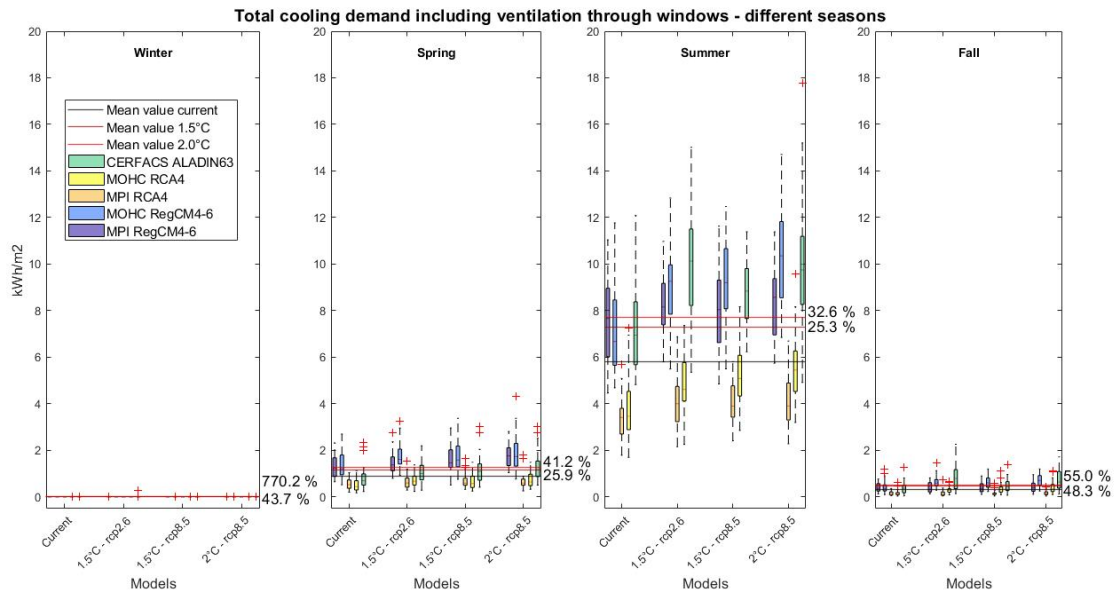


Figure 30: Total cooling demand during different seasons per area unit including ventilation through windows. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

Figure 31 shows the peak cooling demand in each season. Just as expected based on the other results from this thesis is the change in peak cooling demand lower than the total demand. The cooling during the spring and fall is not that different compared to the summer season compared to the difference between the different seasons in total cooling. It seems like a hot day can occur during the spring and fall season as well. If cooling through windows is included the result change in a similar way as in the other cases. The result from peak cooling demand for different seasons when cooling through windows is possible can be seen in Appendix A.9.

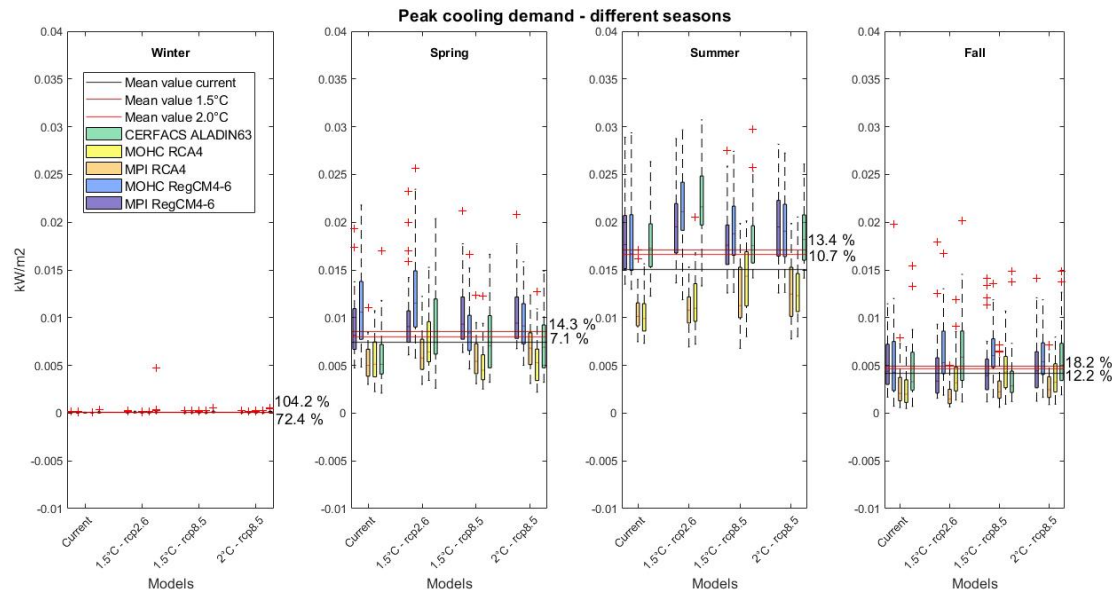


Figure 31: Peak cooling demand during different seasons excluding ventilation through windows per area unit. The black horizontal line marks the average demand in the current scenario, the dark red is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

3.4. Heating period

Figure 32 shows the length of the yearly heating period. The figure shows a summary of how it varies depending on how the end and start of the period is defined. The first plot defines the start of the heating period when 1% of the yearly heating demand has been used and stops when 99% has been used. The second plot starts counting at 2% and stops at 98% and third plot starts at 3% and ends at 97%. The interesting part about this is that in all three cases the trend is very similar. For the 1.5°C climate scenario the heating period is decreased by 1.4-1.6% and for 2.0°C scenario the length of the heating period is decreased by 2.1-2.2%.

The model CERFACS ALADIN63, the green box plot, has shorter heating periods compared to the other models, but it was not the model with the lowest yearly demand of heating. This implies that the model has shorter, but colder winters compared to the other models.

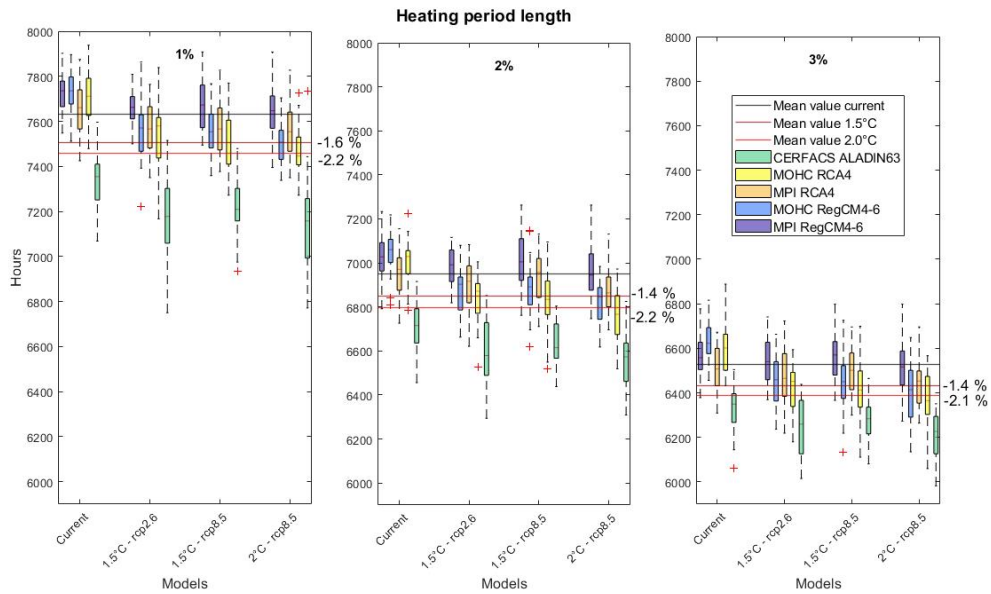


Figure 32: Length of heating period for four different climate scenarios. (Note that the y-axis does not start at 0)

3.5. Demand changes in the different models

Figure 33 shows how the demand changes in each model in every scenario compared to the current case. The total heating demand decreases between 5-13% in the 1.5°C climate scenario. In the 2°C climate scenario the heating demand decreases 11-16% compared to the current scenario. GCM MPI gives the least change due to climate change, while GCM MOHC give a larger change.

Looking at model MPI RCA4, in the plots with and without cooling through windows, the model seems to be constant in all three different climate scenarios.

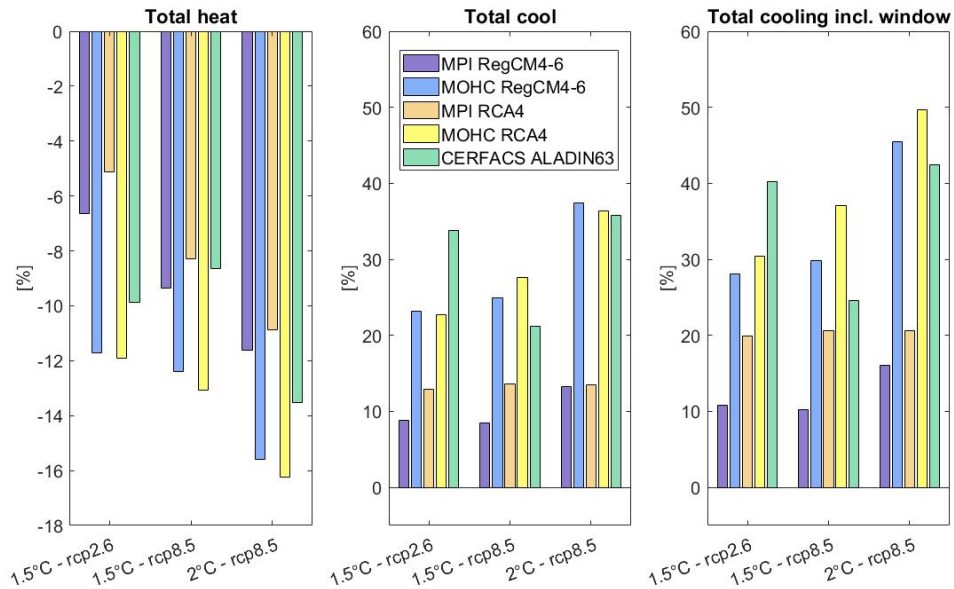


Figure 33: The degree of changed demand for the different models compared to the current demand for each model. The first box is the total heat demand, the second is the cooling demand and the last box is the cooling demand including ventilation through windows. The first scenario in every box is the demand at a global temperature increase of 1.5°C in the RCP 2.6 scenario, the second is 1.5°C temperature increase at RCP 8.5 and the last is 2°C temperature increase at RCP 8.5.

Figure 34 shows how the peak demand in the different models are affected by climate change. All models show a decreased peak heating demand except MPI RCA4 in climate scenario 1.5°C - RCA 2.6 and all models show an increased peak cooling demand except model MPI RegCM4-6 in the RCP 8.5 scenarios. As stated before in Figures 19 and 20 the peak cooling demand increased more between the different climate scenarios at the lower peak levels, in the 99% level all the different models shows an increase between the different climate scenarios. The decrease in peak cooling demand for model MPI RegCM4-6 showing in Figure 34 could therefore be a coincidence. More models should be investigated to be able to be more certain about how climate change affects the peak demand.

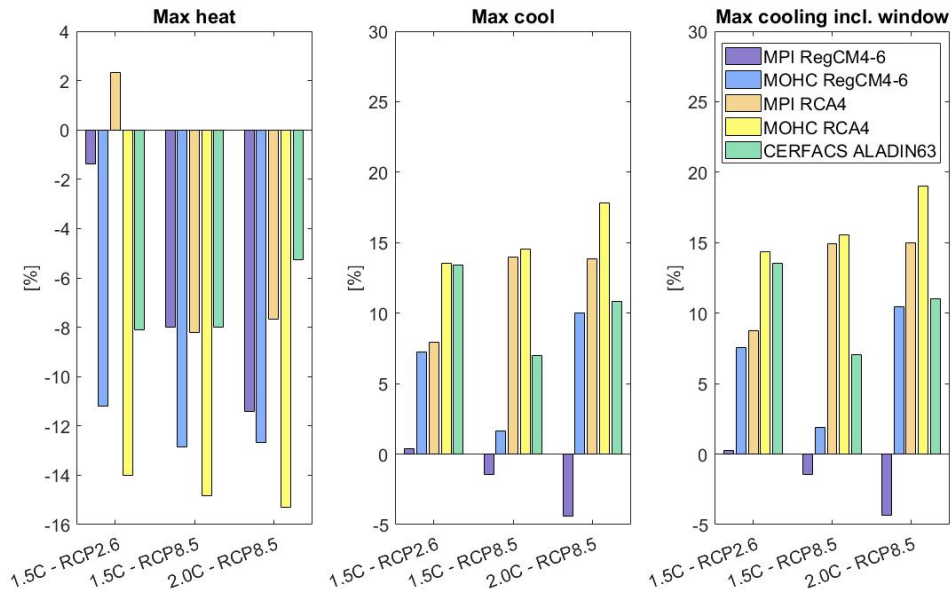


Figure 34: The degree of changed maximum effect for the different models compared to the current maximum effect for each model. The first box is the maximum heat effect, the second is the maximum cooling effect and the last box is the maximum cooling effect including ventilation through windows. The first scenario in every box is the maximum effect at a global temperature increase of 1.5°C in the RCP 2.6 scenario, the second is 1.5°C temperature increase at RCP 8.5 and the last is 2°C temperature increase at RCP 8.5.

4. Discussion

The result from this thesis are based on a line of assumptions to be able to focus the result on how climate change itself impacts the demand. In this section the method used and the results from the thesis is discussed. First an overall discussion about assumptions and limitations are made followed by a discussion regarding the building stock, the climate models and finally the cooling demand. After that the result from this study will be discussed in regards to other studies. Lastly a discussion regarding future research is made.

4.1. Assumptions and limitations

In the real world, there are several other important aspects that will impact the future demand other than climate change. These aspects can be parameters regarding trends in the building industry, standard of living among the population, economical and behavioral aspects and so on. All aspects are hard to capture with the time limitations of this thesis, but there are other studies made regarding these aspects. The aim of this thesis was not to investigate that part further, but to focus on the impact of climate change.

4.1.1. Building stock data

The building stock was assumed to be constant during all years modelled in this thesis to be able to focus the result on how climate change affects the demand. The building stock used was a combination of a representation of the SFD in 2016 and the MFD and NRB in 2006. A representation of the building stock existing in year 1985 would have made it easier to make comparisons between the actual demand in 1985 and the results from the different models. It would have been interesting to see which model was closest to reality at start, but since the focus was the change in demand between different levels of global warming and not the actual demand, a different building stock would not have impacted the results in the thesis.

The data regarding the NRB was not as detailed as the SFD and MFD data. The NRB data did not include as much information about the buildings' thermal properties as the SFD and MFD. Because of that the one stage energy balance model was used for the NRB. This did probably not affect the result too much since the focus was the change in demand between the different climate scenarios, but the result would have been more precise if the required information for the two-stage energy balance was available for the NRB as well.

The NRB were divided into three different geographical locations, compared to the 30 locations of the SFD and MFD. To divide the NRB over more locations would have made it easier to divide the entire building stock into the same regions and the comparison between the national and the regional demand would have been easier to make.

The locations of the buildings were matched to the closest climate data node. The buildings only have 30 different locations assigned to them while the climate data nodes are spread out over Sweden with 10-50 km distance between each node. In that aspect, the amount of the available climate data in each model used in this thesis is very low. The data nodes included in the thesis might have been points with extreme weather conditions affecting the result in one way or the other. The best result could have been achieved by dividing the building stock over as many climate nodes as possible while also keeping demographic aspects in mind.

4.1.2. Climate models

There is a lot to say about the climate data used in this thesis. The more climate models used, the better the quality of the result. However due to time constraints it was not possible to manage more than five models. With more models, it would have been possible to look closer at the actual demand and not just how it changes between different scenarios.

This thesis only investigates four different climate scenarios, the current scenario, 1.5°C and RCP 2.6 scenario, 1.5°C and RCP 8.5 scenario and 2°C and RCP 8.5 scenario. It would have been interesting to see what happens at higher levels of global warming. A RCP 4.5 scenario may not be as interesting since the difference between the results from scenario RCP 2.6 and RCP 8.5 did not differ that much. On the other hand, there might be more difference between RCP 4.5 and RCP 8.5 in climate scenario 2°C than the difference between scenario 1.5°C – RCP 2.6 and 1.5° RCP 8.5. With that in mind RCP 4.5 might be an interesting scenario as well.

4.1.3. Cooling demand

There are more aspects than climate change itself that needs to be investigated to be able to know the future cooling demand. The results showed that the demand for comfort cooling increased when the average global temperature increase. It is hard to say whether the cooling would increase in the same way in the real world. One reason for that is the other parameters that drives the incentives for installing cooling systems. As mentioned previously it is connected to economic aspects, trends, status, standard of living and time spent at home other than climate change itself.

The last three summers in Sweden have been very hot, and it has resulted in more households investing in different kinds of cooling systems, but still far from every building having a cooling system installed. In the results from the energy balance model every building had a cooling system installed by year 1990 in climate model MPI RegCM4-6, which is not the case in reality. Since the results in the thesis are based on health recommendations regarding indoor air temperature, it gives a good estimation of how it could affect the climate even though other aspects are important for the real outcome.

Li et al. mentions in the study “Low carbon heating and cooling of residential buildings in cities in the hot summer and cold winter zone-A bottom-up engineering stock modeling approach” that cooling systems might not be used in an entire building, but only in the parts of the building that residents spend most of their time, for example the bedroom, living room and kitchen. This thesis did not include that aspect of the cooling demand. This will not only affect the amount of cooling needed but also the development. A small cooling system in the bedroom can be a first step towards a cooling system that eventually covers the whole building. This aspect will therefore affect the impact due to climate change seen in the result section.

One other aspect is how an implemented cooling system is used. The maximum allowed indoor air temperature defined for buildings with a cooling system in the thesis is 26°C based on the Swedish Public Health Authorities recommendations [15], but when a cooling system is installed, the behavioral aspects become important to know the demand. The user patterns can be everything from using it every day to only certain hours. The user might be happy with the 26°C indoor air temperature limit, while others do not want an indoor air temperature above 22°C. These aspects are very important to keep in mind when looking at the results from this thesis.

4.1.4. The energy balance model

The possibility to cool down buildings was implemented after the optimization model. This means that the amount of cooling that could be sustained from open windows was not part of the optimization. If it were part of the optimization buildings could have been strategically cooled down to the lower part of the allowed indoor air temperature span to prevent usage of cooling systems. If open windows would have been part of the optimization model the results regarding the change in cooling demand would probably be lower.

4.2. Comparison to the old study

In Appendix B Chapter 11 from the final report from the Swedish Commission of Climate and Vulnerability [26] the changed heat demand was calculated between 2011-2040, 2041-2070 and 2071-2100 compared to the current demand in 2007. Since the result from the report were based on the difference between different time periods it is hard to say what level of global warming that represent in comparison to the results in this thesis. The report does also have another reference year compared to this.

4.3. Energy performance targets of buildings

The National programme for energy efficiency and energy-smart construction states that the emission from Swedish buildings was responsible for 38% of Sweden's total energy use in 2003 [3, 27]. There is a target of decreasing the energy use in buildings by 20% by 2020 and 50% per heated floor area by 2050 compared to the energy use in 1995 [27]. The 2°C climate scenario is dated before 2050 for all models, meaning climate change could affect the demand in the way that has been calculated in this thesis. When adding the change in heating and cooling demand together it is a total change of shortly below 10% decrease in energy demand between year 1985 and the 2°C - RCP 8.6 scenario. The combined change of heating and cooling demand in climate scenario 1.5°C is almost 8% compared to 1985.

4.4. Future research

As mentioned in the sections above there are many ways to develop the work in this thesis to make it more certain and closer to reality. The number of climate nodes, climate models and climate scenarios are some aspects connected to development regarding the climate data. The possible changes to the building stock data could possibly bring some value in another project. Cooling through windows can be a part of the optimization model to prevent implementation of cooling systems.

With more climate data, the development of demand profiles that represents different kinds of climates is possible. This is something that would be valuable in other studies about the future demand.

5. Conclusion

It is difficult to say what the future will hold with 100% certainty, but this thesis could give some sort of insight on what direction the demand is changing due to different levels of global warming.

The 1.5°C and 2°C climate scenario have similar effects on the future demand, but in different magnitudes. Meaning they both affect the demand in the same direction, but the effects from the 2°C climate scenario are greater than in the 1.5°C.

The total heating demand is decreased 9.7% and 13.6% for the 1.5°C and 2°C climate scenario. The largest change in heating demand occurs during the winter season and the least during the summer season for all climate scenarios. The heating demand per heated floor area continues to be the largest in the northern parts of Sweden in all the different climate scenarios. The regions with the highest yearly demand is the regions where the biggest part of the building stock is located. The heating period is slightly decreased in both climate scenarios.

The peak heating demand is slightly less affected by climate change compared to the yearly total heating demand. The yearly peak heating demand decreases 8.6% and 10.5% for climate scenario 1.5°C and 2°C respectively. The highest 4% of the peak hours appear to be affected by the climate the same way as the highest peak. This implies that the variation of the top 4% highest yearly peak demand hours does not change between the different scenarios.

The total yearly cooling demand increases 21.1% and 27.6% in climate scenario 1.5°C and 2°C respectively. The largest demand increase per square meter heated floor area happens in the northern parts of Sweden. The largest amount of the yearly increase happens during the summer time.

The yearly peak cooling demand is over all slightly less affected by climate change compared to the yearly cooling demand. The yearly peak is increased 11.2% and 14.8% in the 1.5°C and 2°C climate scenario respectively. The highest 4% of the demand hours are affected in different ways. The highest 1% is less affected than the lowest peak of the 4%. This implies that the variations in the highest peak hours will decrease with a warmer climate.

The possibility to open windows to cool down buildings decreases the cooling demand and the peak cooling demand compared to the case were cooling through windows is not possible. The demand change between climate scenario current and 1.5°C, and current and 2°C is larger in the case were window cooling is possible. In climate scenario 2°C were

the biggest change is seen, but the amount cooling needed in that scenario is still lower than the 1.5°C scenario in the case without cooling through windows. The NRB cooling demand is not as affected by the possibility to cool down the building by open windows as the SFD and MFD cooling demand is.

The calculation regarding the future heating and cooling demand varies between the different climate models used in this work. Although they all point in the same direction of change when the average global temperature increases. Every climate model used results in a decreased heating demand, between 5%-16% decrease depending on climate model and scenario, and an increased cooling demand, between 9%-38% depending on climate model and scenario. The overall change in the yearly combined energy needed for heating and cooling in the building stock decreased around 8% between the current and 1.5°C climate scenario and 10% between the current and the 2°C climate scenario.

References

- [1] Sweden's Meteorological and Hydrological Institute (SMHI), "Klimatindikator - temperatur," 2020, available at: <https://www.smhi.se/klimat/klimatet-da-och-nu/klimatindikatorer/klimatindikator-temperatur-1.2430> [2020-07-21].
- [2] Statens Energimyndighet, "Energiläget i siffror," *Statens Energimyndighet*, 2020.
- [3] D. Romanchenko, E. Nyholm, M. Odenberger, and F. Johnsson, "Balancing investments in building energy conservation measures with investments in district heating - A Swedish case study," *Energy and Buildings*, p. 110353, 2020.
- [4] Statens Energimyndighet, "Energiläget 2020," 2020, available at: <http://www.energimyndigheten.se/nyhetsarkiv/2020/energilaget-2020---en-samlad-bild-pa-energiomradet-i-sverige/> [2020-06-04].
- [5] —, "Energistatistik för lokaler 2018," 2019, available at: <http://www.energimyndigheten.se/statistik/den-officiella-statistiken/statistikprodukter/energistatistik-for-lokaler/> [2020-07-21].
- [6] C. Y. Yi and C. Peng, "An archetype-in-neighbourhood framework for modelling cooling energy demand of a city's housing stock," *Energy and Buildings*, vol. 196, pp. 30–45, 2019.
- [7] I. S. Dobosi, C. Tanasa, N.-E. Kaba, A. Retezan, and D. Mihaila, "Building energy modelling for the energy performance analysis of a hospital building in various locations," in *E3S Web of Conferences*, vol. 111. EDP Sciences, 2019.
- [8] X. Li, R. Yao, W. Yu, X. Meng, M. Liu, A. Short, and B. Li, "Low carbon heating and cooling of residential buildings in cities in the hot summer and cold winter zone - A bottom-up engineering stock modeling approach," *Journal of Cleaner Production*, vol. 220, pp. 271–288, 2019.
- [9] J. Gode, J. Axelsson, S. Eriksson, K. Holmgren, G. Hovsenius, E. Kjellström, P. Larsson, L. Lundström, and G. Persson, *Tänkbara konsekvenser för energisektorn av klimatförändringar - Effekter, sårbarhet och anpassning*, 2007.
- [10] V. M. Nik and A. S. Kalagasidis, "Impact study of the climate change on the energy performance of the building stock in stockholm considering four climate uncertainties," *Building and Environment*, vol. 60, pp. 291–304, 2013.

-
- [11] É. Mata, J. Wanemark, V. M. Nik, and A. S. Kalagasidis, “Economic feasibility of building retrofitting mitigation potentials: Climate change uncertainties for Swedish cities,” *Applied Energy*, vol. 242, pp. 1022–1035, 2019.
- [12] É. Mata, A. S. Kalagasidis, and F. Johnsson, “A modelling strategy for energy, carbon, and cost assessments of building stocks,” *Energy and Buildings*, vol. 56, pp. 100–108, 2013.
- [13] E. Nyholm, *The role of Swedish single-family dwellings in the electricity system - The importance and impacts of solar photovoltaics, demand response, and energy storage*. Chalmers Tekniska Hogskola (Sweden), 2016.
- [14] E. Mata and A. S. Kalagasidis, “Calculation of energy use in the Swedish housing,” *Chalmers Univeristy of Technology, Gothenburg, Sweden*, vol. 2009, p. 4, 2009.
- [15] Folkhälsomyndigheten, “Folkhälsomyndighetens allänna råd om temperatur inomhus FoHMFS 2014:17,” 2014.
- [16] World Health Organization (WHO), “Information and public health advice: heat and health.” 2018, available at: <https://www.who.int/globalchange/publications/heat-and-health/en/> [2020-10-07].
- [17] T. I. Hennemuth, D. Jacob, E. Keup-Thiel, S. Kotlarski, G. Nikulin, J. Otto, D. Rechid, K. Sieck, S. Sobolowski, P. Szabó *et al.*, “Guidance for EURO-CORDEX climate projections data use,” *Version 1. 0-2017.08. Retrieved on*, vol. 6, p. 2019, 2017.
- [18] WCRP Coordinated Regional Climate Downscaling Experiment, “About - CORDEX,” 2020, available at: <https://cordex.org/about/> [2020-08-17].
- [19] World Meteorological Organization (WMO), “FAQs - climate,” 2020, available at: <https://public.wmo.int/en/about-us/FAQs/faqs-climate> [2020-06-28].
- [20] G. Nikulin, C. Lennard, A. Dosio, E. Kjellström, Y. Chen, A. Hänsler, M. Kupiainen, R. Laprise, L. Mariotti, C. F. Maule *et al.*, “The effects of 1.5 and 2 degrees of global warming on Africa in the CORDEX ensemble,” *Environmental Research Letters*, vol. 13, no. 6, p. 065003, 2018.
- [21] Boverket. (2018) Öppna data - Betsi är en undersökning om byggnaders tekniska status. Available at: <https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/oppna-data/betsi-oppna-data/>, [2020-02-27].

-
- [22] J. Grundsell, “Bottom-up description of the Swedish non-residential building stock - Archetype buildings and energy demand,” Master’s thesis, 2013.
- [23] E. Nyholm, S. Puranik, É. Mata, M. Odenberger, and F. Johnsson, “Demand response potential of electrical space heating in Swedish single-family dwellings,” *Building and Environment*, vol. 96, pp. 270–282, 2016.
- [24] Boverket, “Regelsamling för byggande, BBR 2012,” 2011, available at: <https://www.boverket.se/contentassets/b7aa3b9e97a0408a8f0f7bbeee3c27e5/regelsamling-for-byggande-bbr-2012.pdf> [2020-06-18].
- [25] Sweden’s Meteorological and Hydrological Institute (SMHI), “Globala temperaturnivåer,” 2020, available at: <https://www.smhi.se/klimat/framtidens-klimat/uppvarmningsnivaer/> [2020-08-17].
- [26] B. Holgersson, T. Hedlund, S. Ahlroth, C. Frost, P. Rosenqvist, and P. Thörn, “Sverige inför klimatförändringarna - Hot och möjligheter (sou 2007: 60),” 2017.
- [27] Ministry of Sustainable development of Sweden, “National programme for energy efficiency and energy-smart construction,” 2006.

A. Appendix 1

A.1. Total yearly heating demand

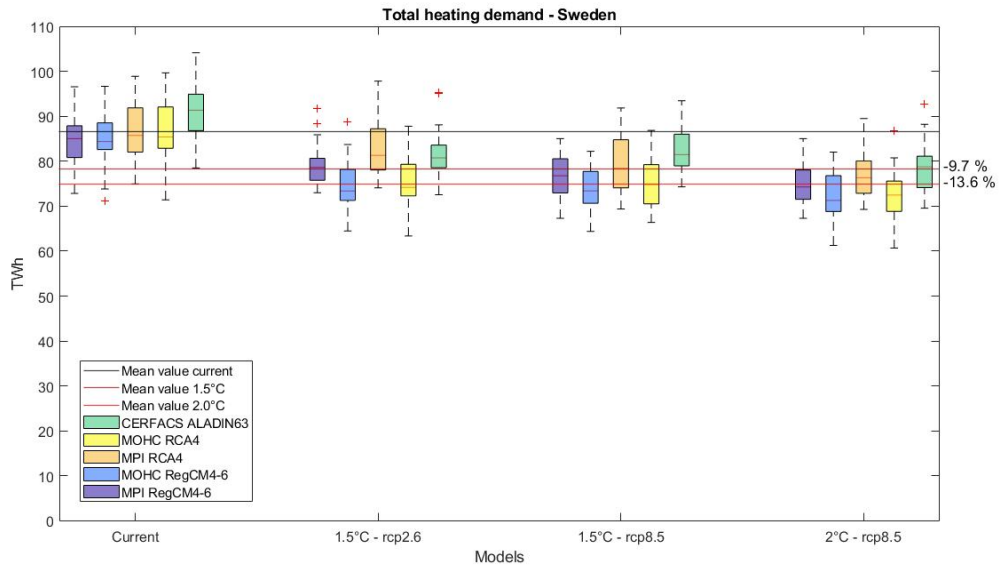


Figure 35: Total yearly heating demand in the Swedish building stock for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

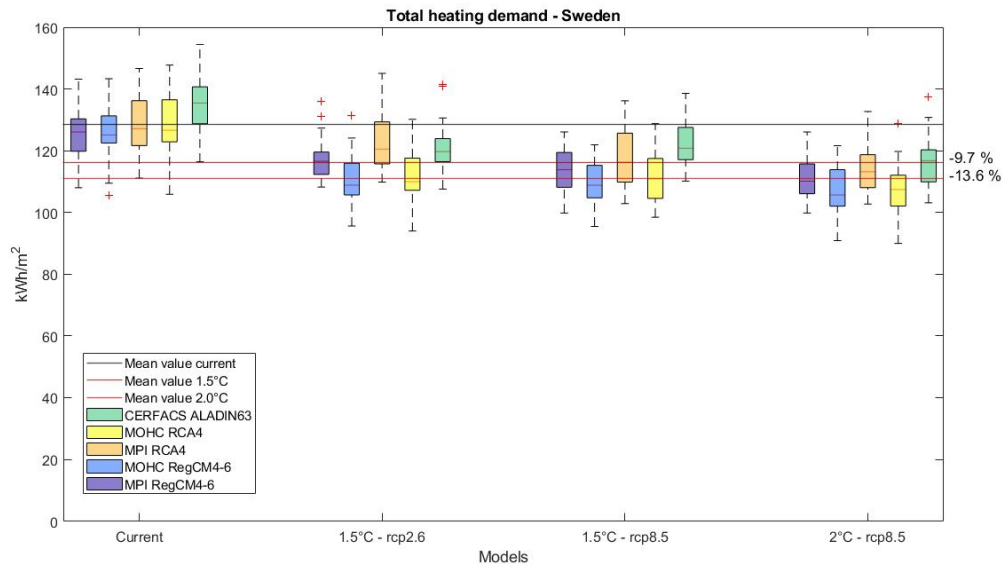


Figure 36: Total yearly heating demand in the Swedish building stock per heated floor area for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

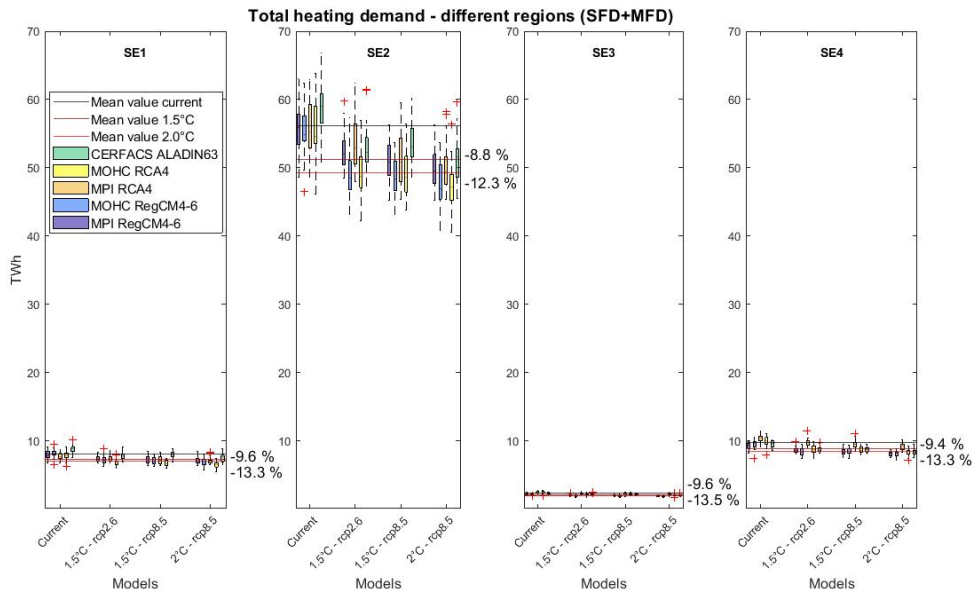


Figure 37: Total yearly heating demand in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

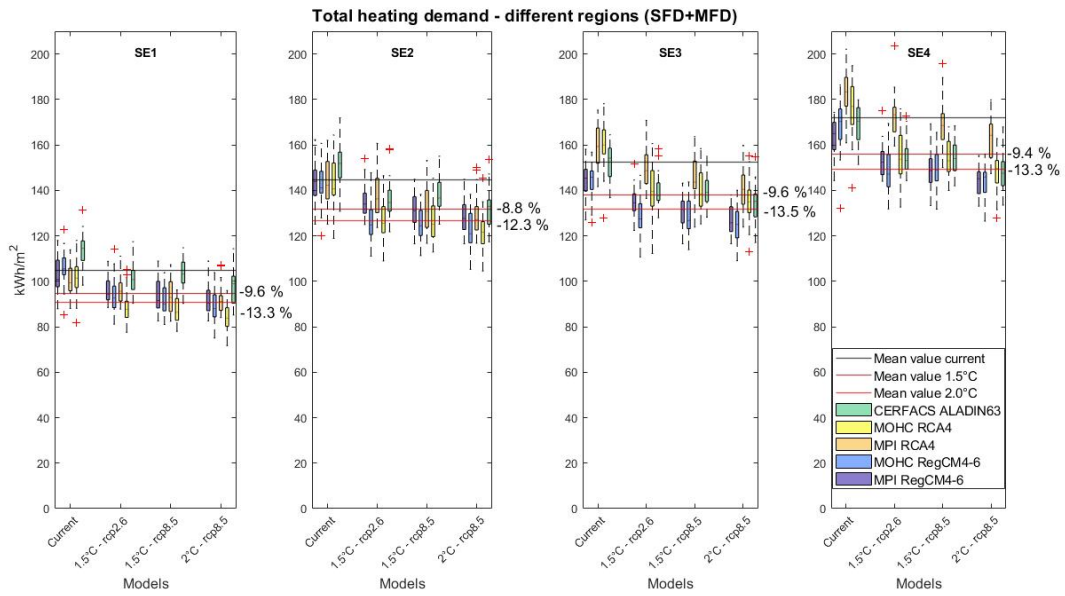


Figure 38: Total yearly heating demand per heated floor area in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

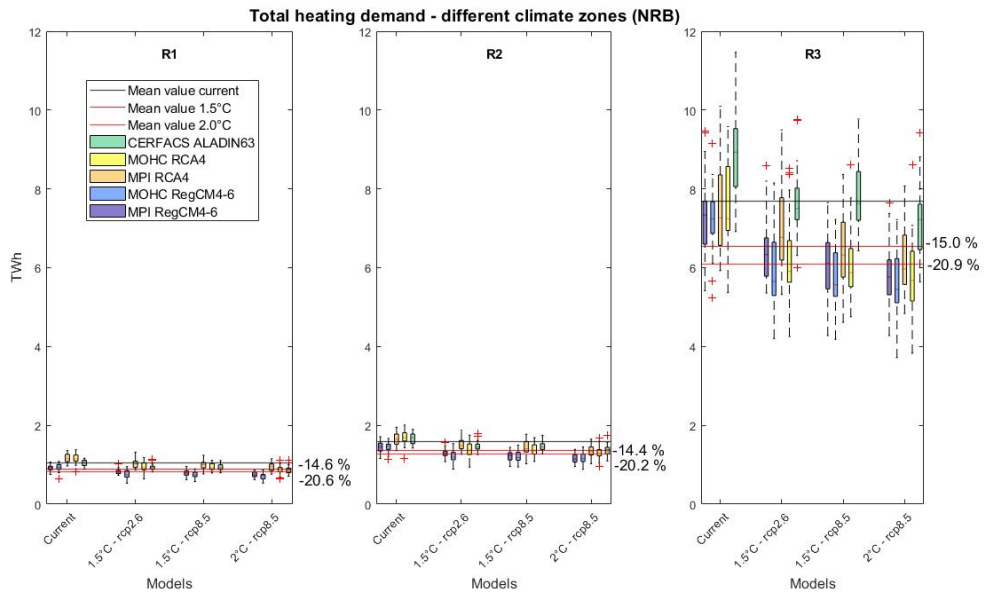


Figure 39: Total yearly heating demand in the different regions R1, R2 and R3, only including NRB, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

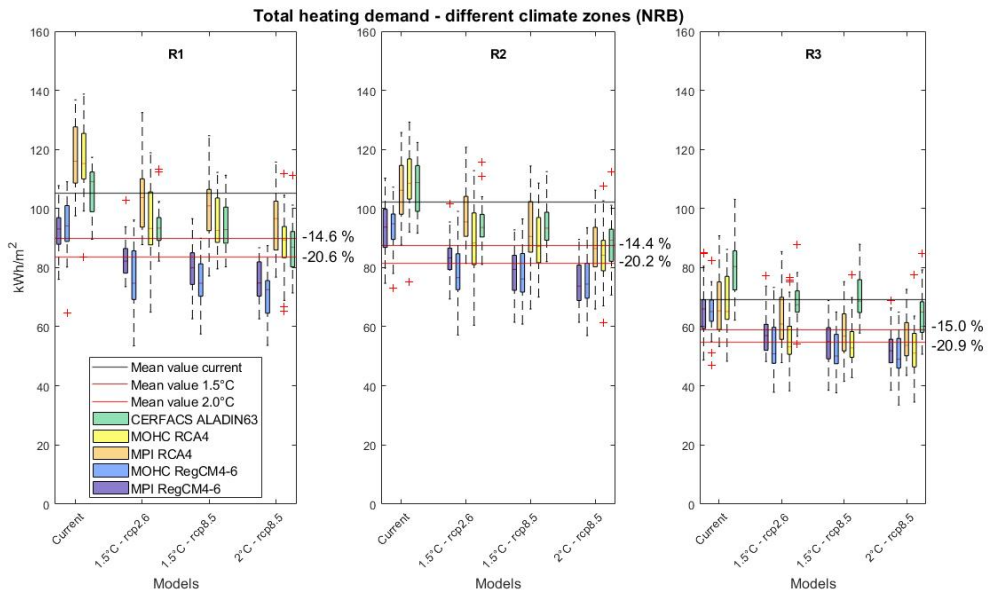


Figure 40: Total yearly heating demand per heated floor area in the different regions R1, R2 and R3, only including NRB, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

A.2. Total heating demand per season

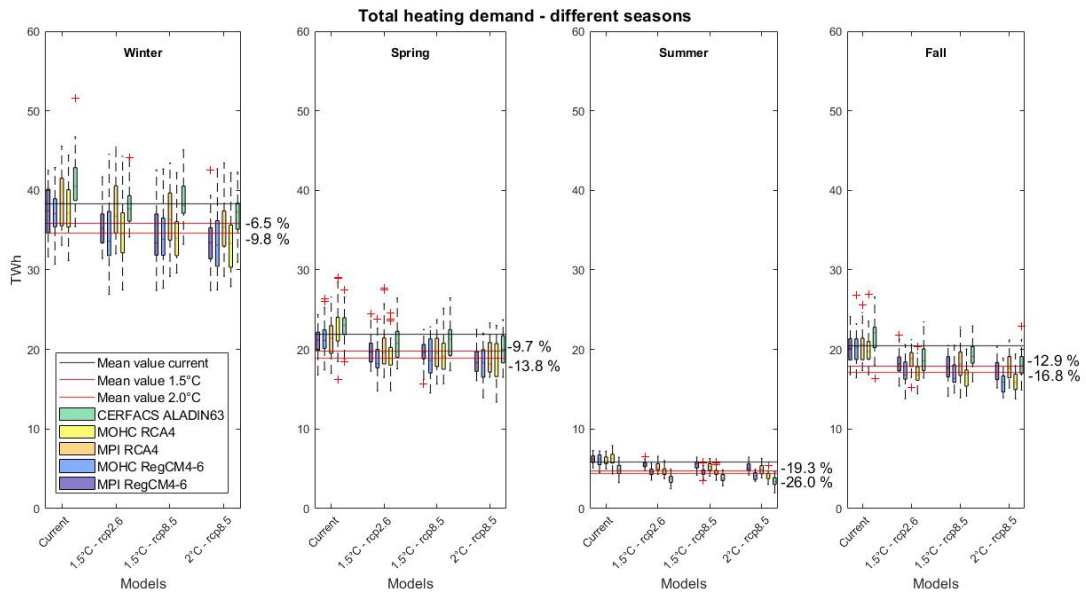


Figure 41: Total seasonal heating demand in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

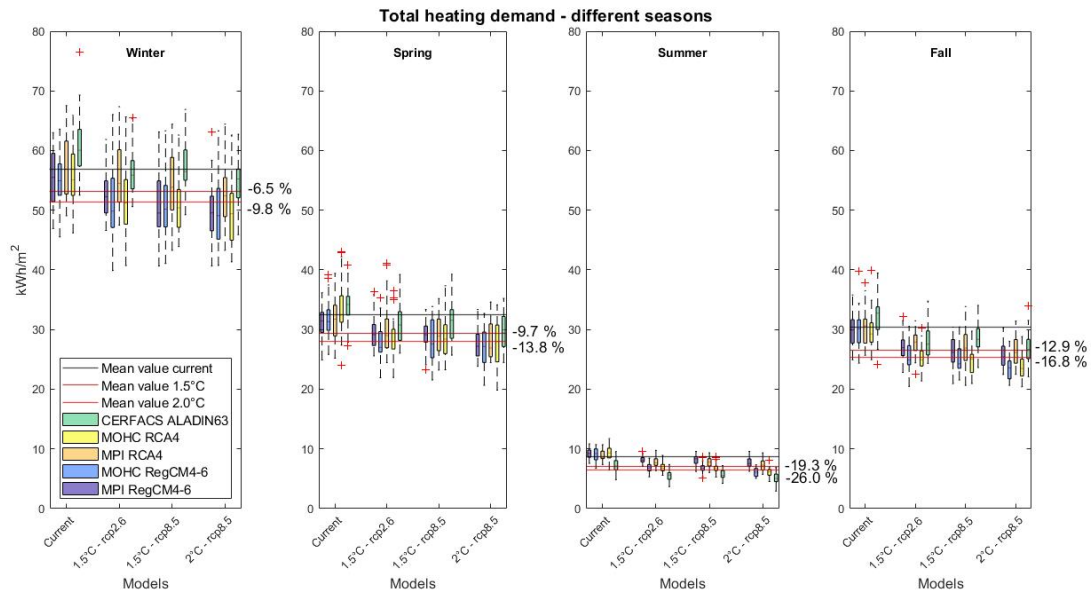


Figure 42: Total seasonal heating demand per heated floor area in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

A.3. Total yearly cooling demand

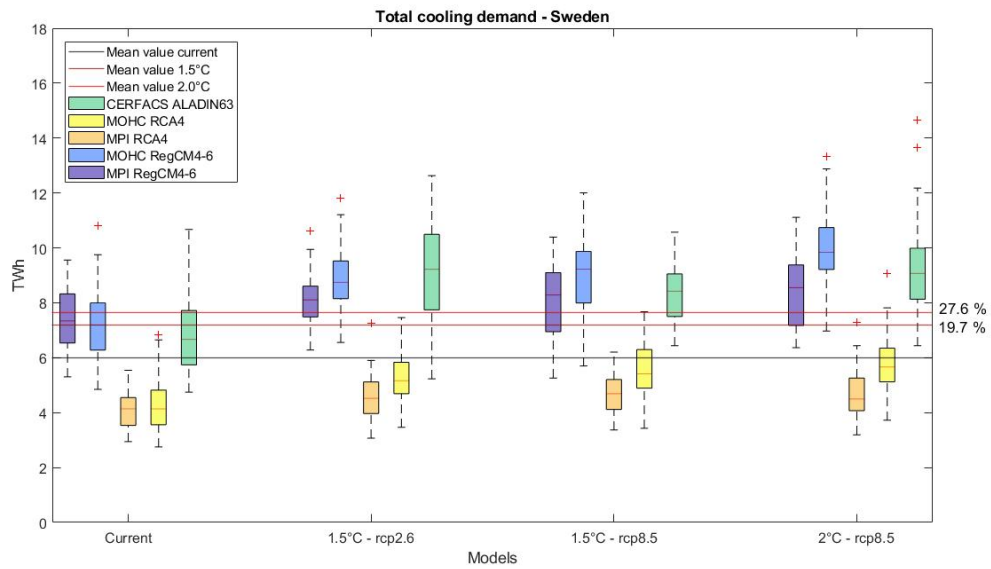


Figure 43: Total yearly cooling demand in the Swedish building stock for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows.

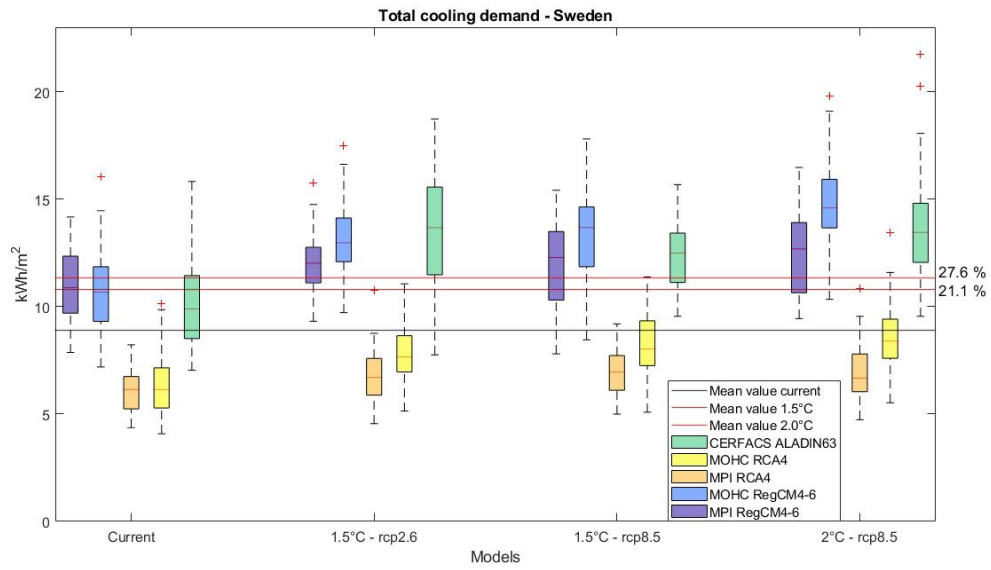


Figure 44: Total yearly cooling demand in the Swedish building stock per heated floor area for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows.

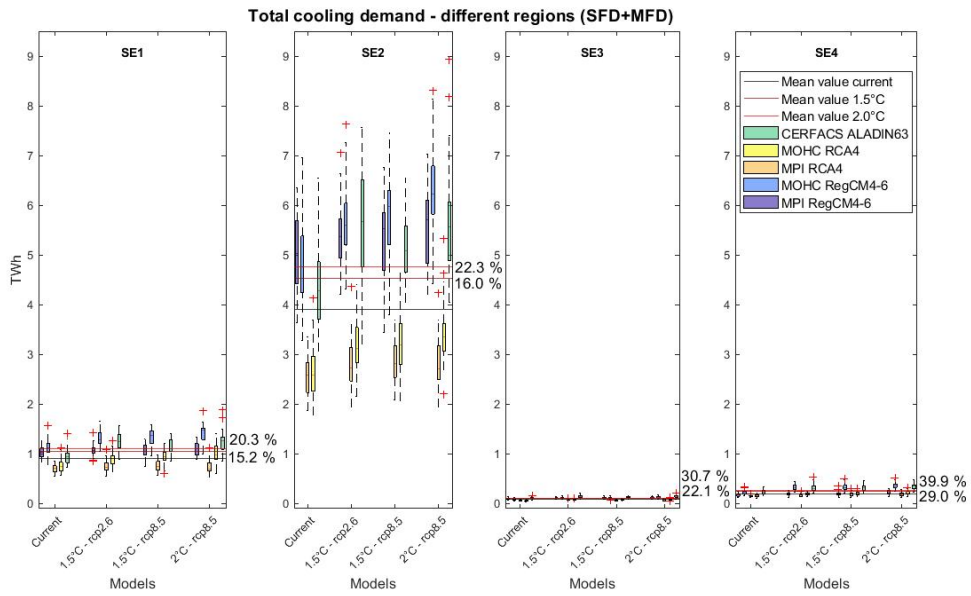


Figure 45: Total yearly cooling demand in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows.

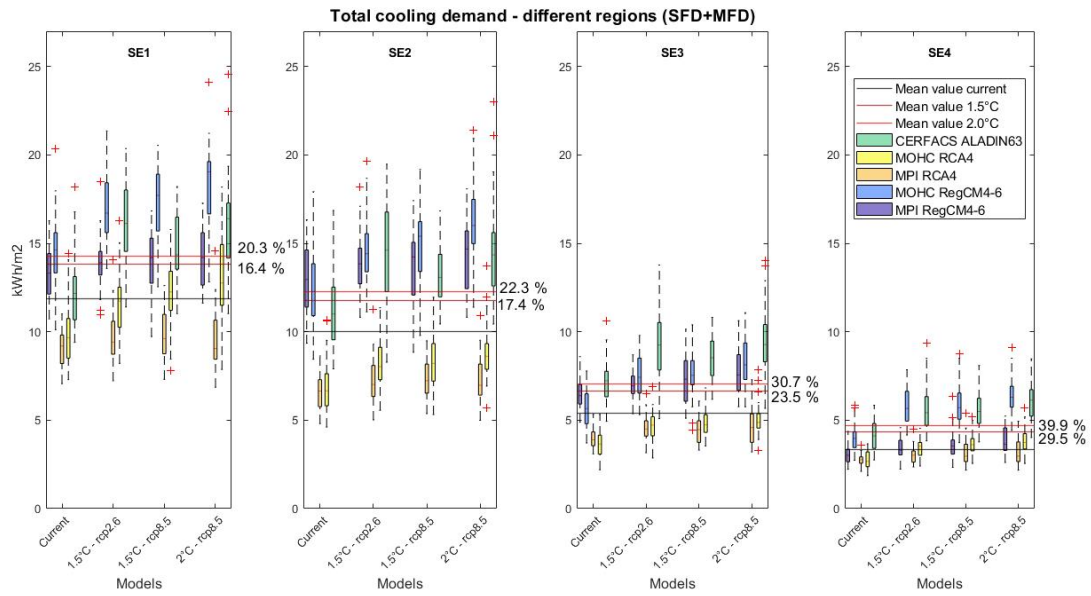


Figure 46: Total yearly cooling demand per heated floor area in the different regions SE1, SE2 SE3 and SE4, only including SFD and MFD for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows.

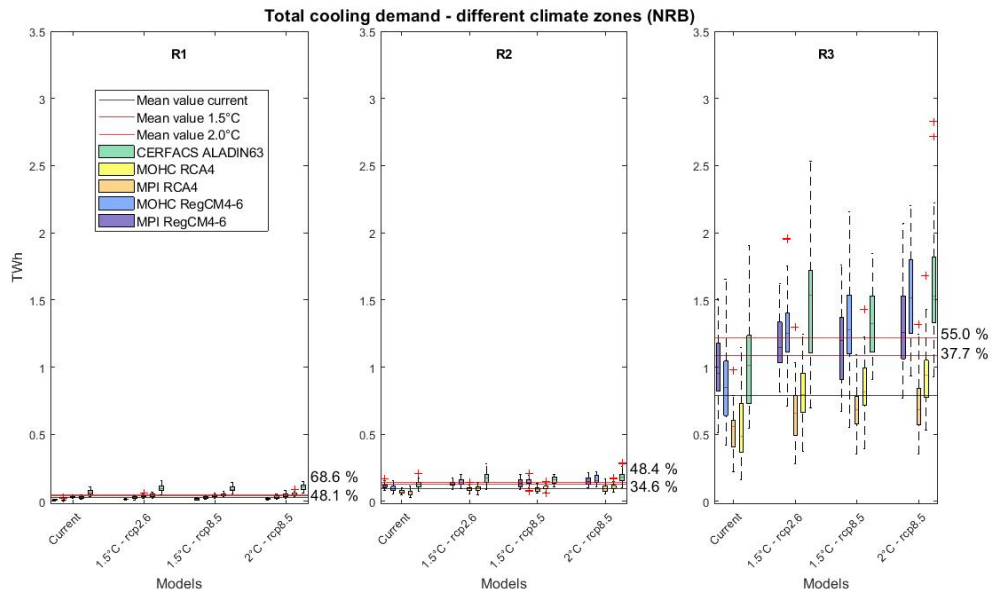


Figure 47: Total yearly cooling demand in the different regions R1, R2 and R3, only including NRB for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows.

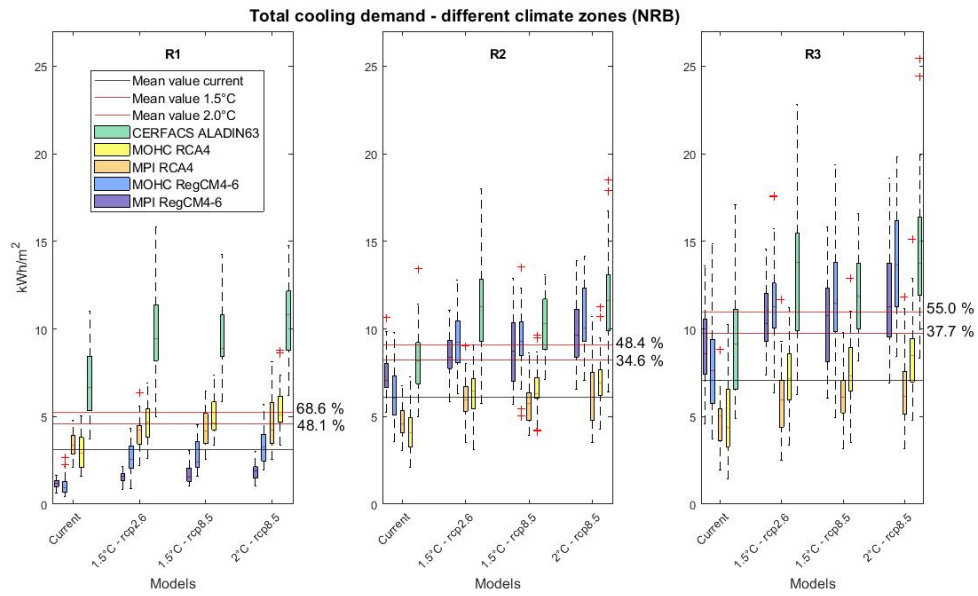


Figure 48: Total yearly cooling demand per heated floor area in the different regions R1, R2 and R3, only including NRB for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows.

A.4. Total cooling demand per season

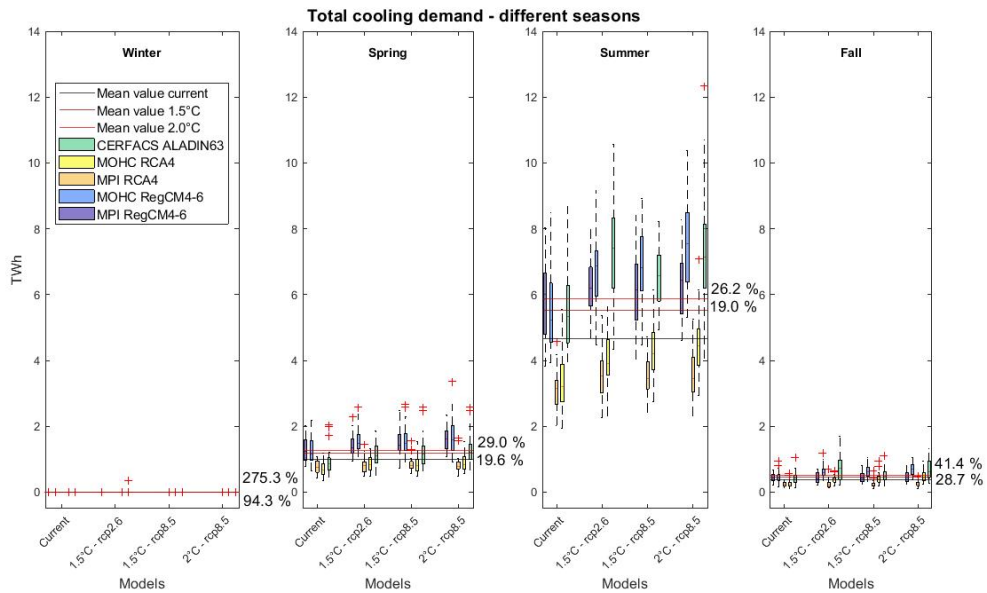


Figure 49: Total seasonal cooling demand in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows.

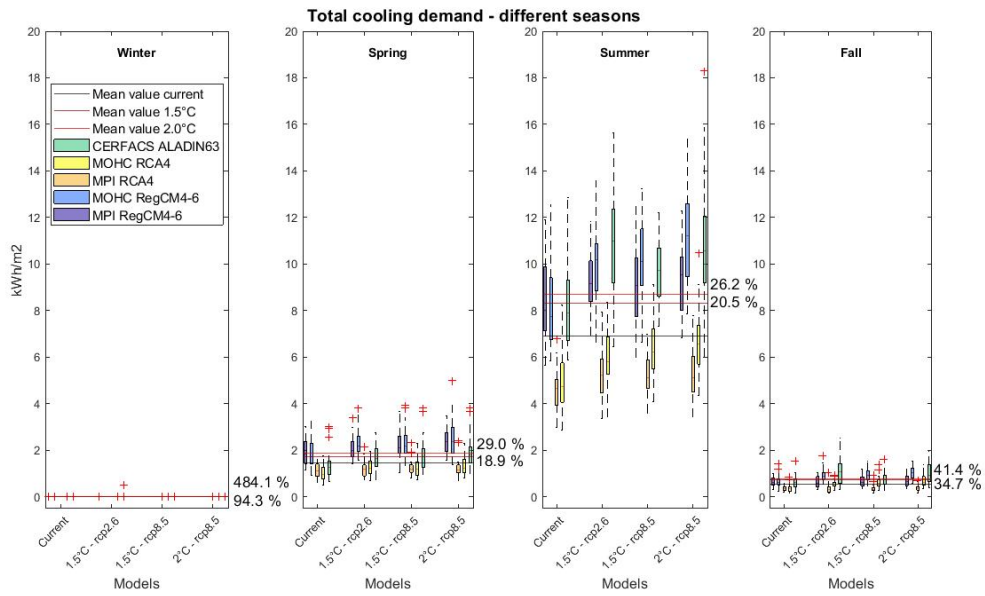


Figure 50: Total seasonal cooling demand per heated floor area in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario. Excluding ventilation through windows.

A.5. Total yearly cooling demand including ventilation through windows

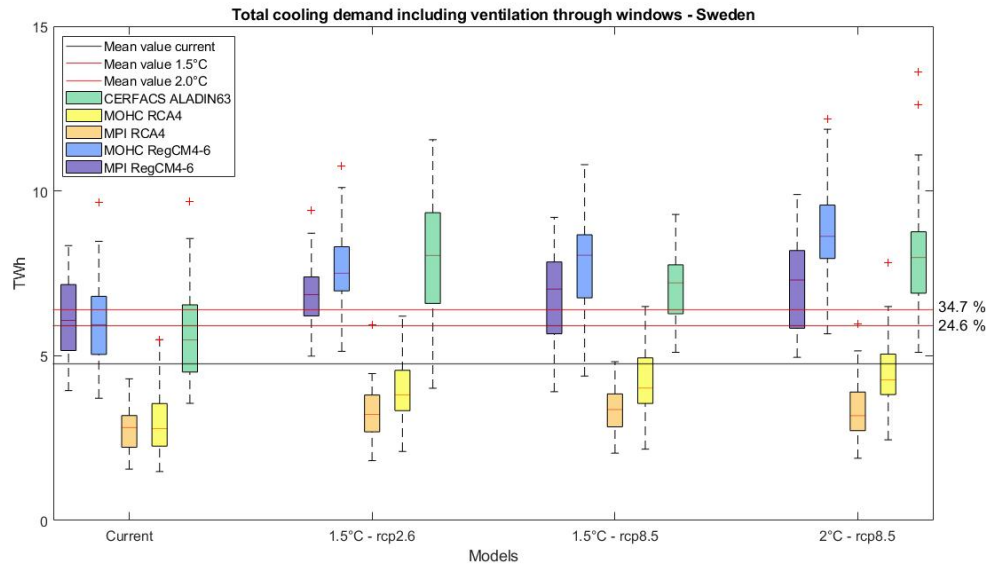


Figure 51: Total yearly cooling demand in the Swedish building stock including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

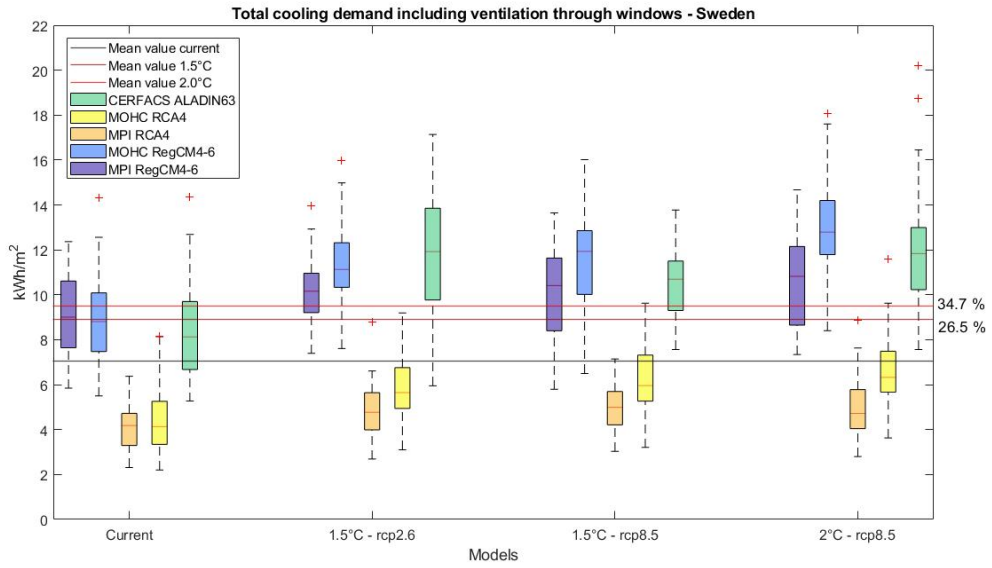


Figure 52: Total yearly cooling demand in the Swedish building stock per heated floor area including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

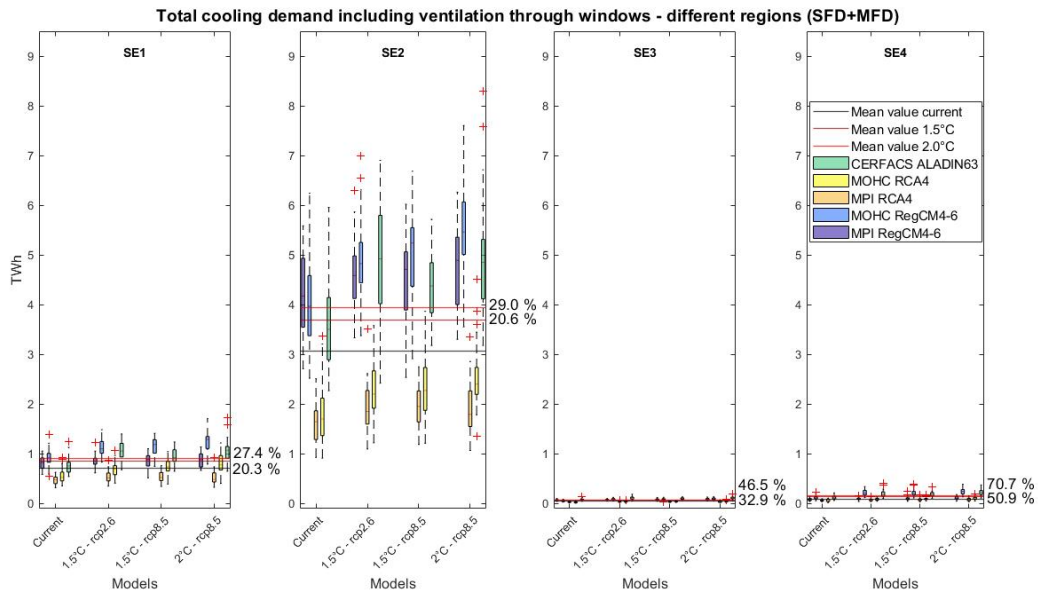


Figure 53: Total yearly cooling demand including natural ventilation in the different regions SE1, SE2, SE3 and SE3, only including SFD and MFD and including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

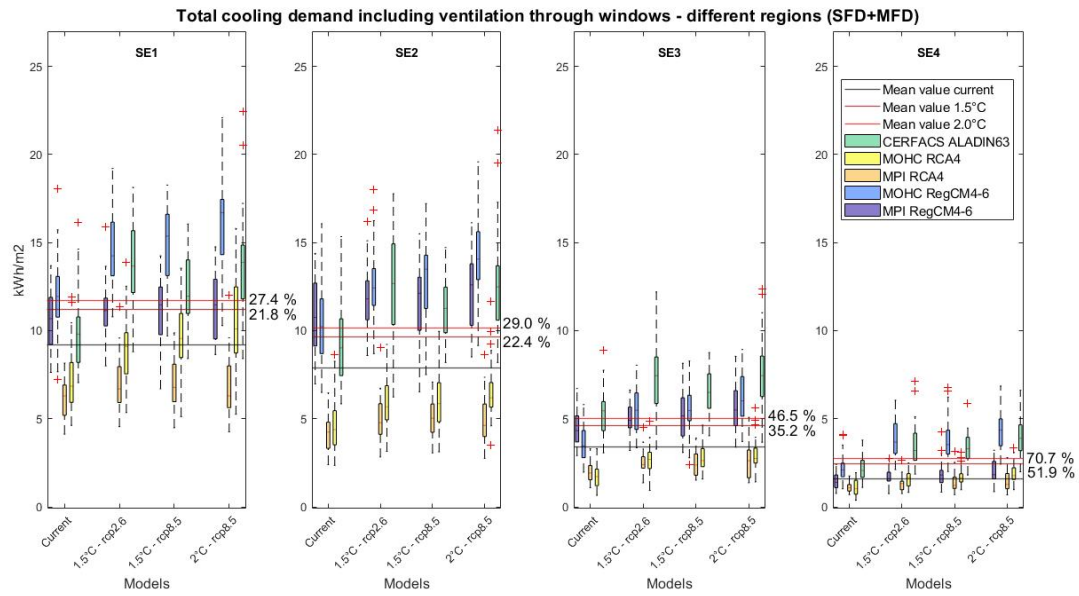


Figure 54: Total yearly cooling demand heated floor area in the different regions, only including SFD and MFD and including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

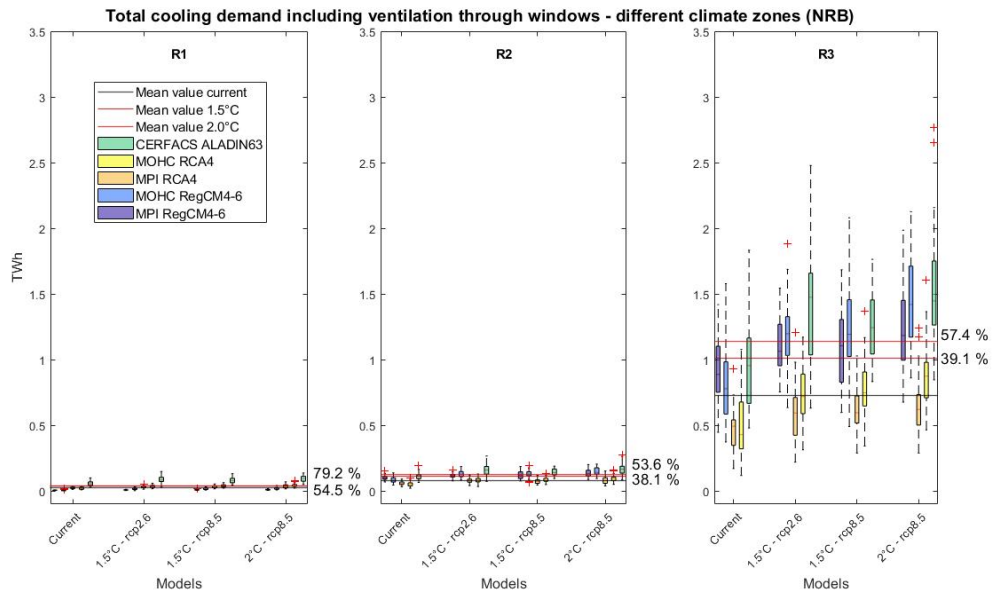


Figure 55: Total yearly cooling demand in the different regions R1, R2 and R3, only including NRB and including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

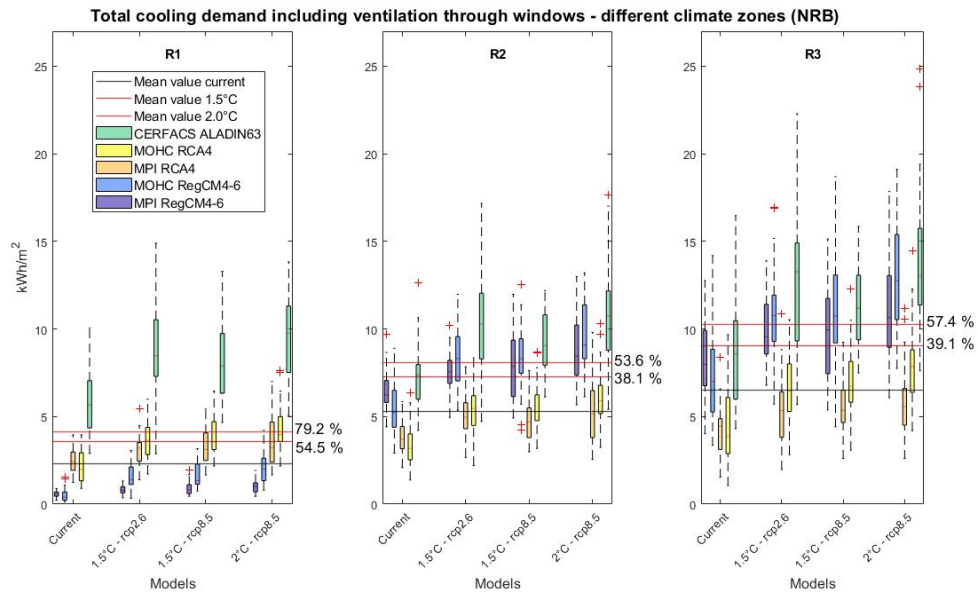


Figure 56: Total yearly cooling demand per heated floor area in the different regions R1, R2 and R3, only including NRB and including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

A.6. Total cooling demand per season including ventilation through windows

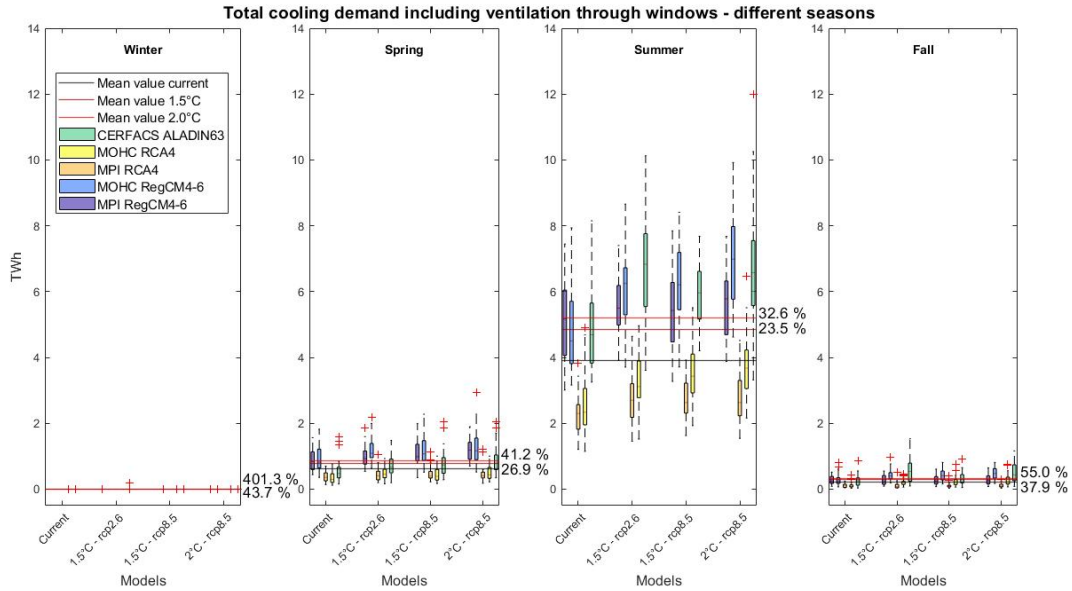


Figure 57: Total seasonal cooling demand in the winter, spring, summer and fall season, including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

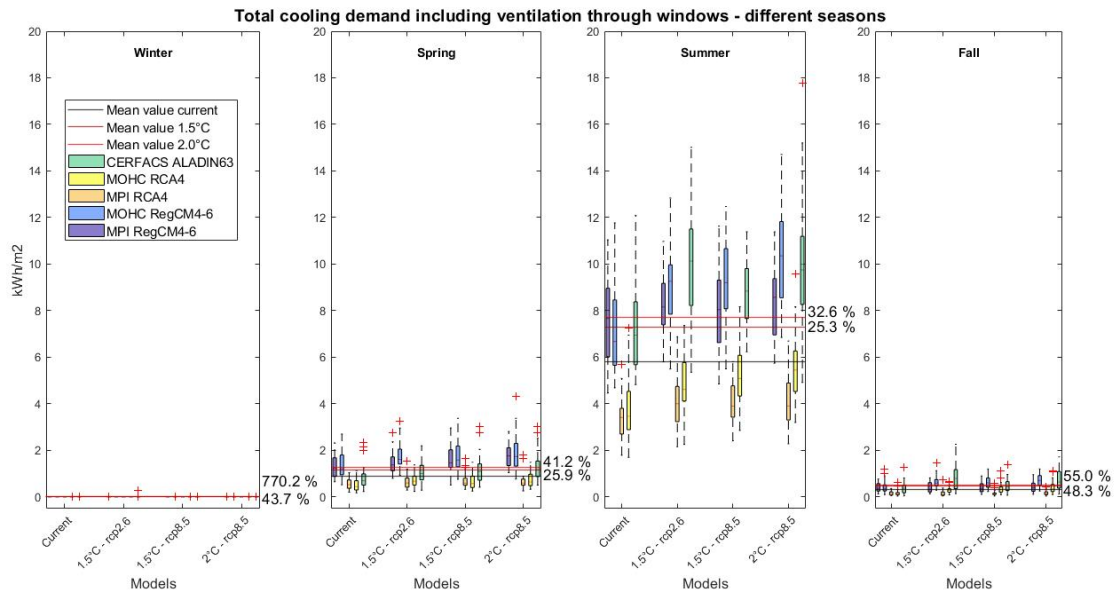


Figure 58: Total seasonal cooling demand per heated floor area in the winter, spring, summer and fall season, including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

A.7. Max effect heating demand

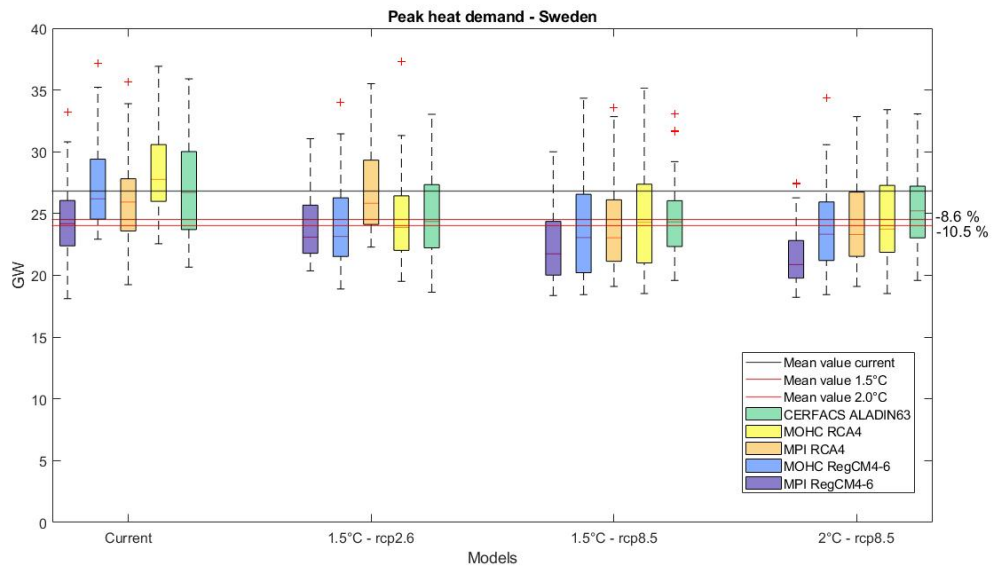


Figure 59: Yearly peak heating demand in the Swedish building stock for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

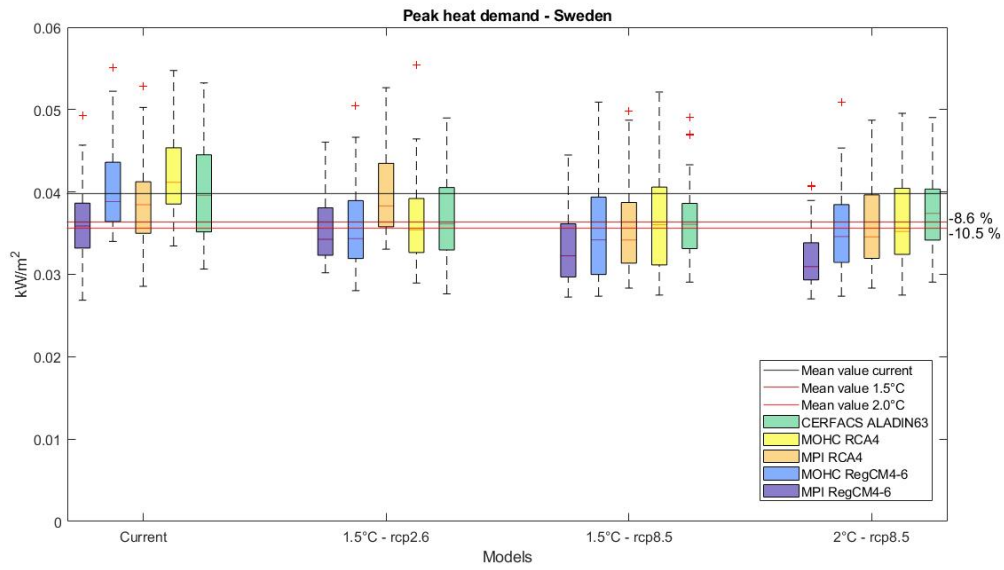


Figure 60: Yearly peak heating demand in the Swedish building stock per heated floor area for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

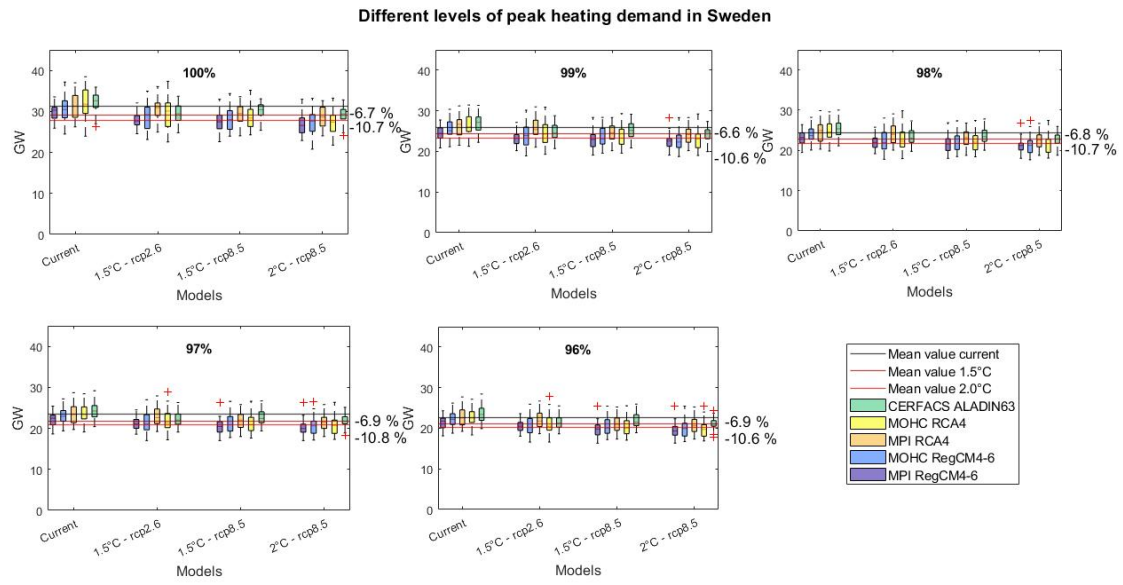


Figure 61: 4% of the yearly highest peak heating demand in the Swedish building stock. The different plots show how the climate is affecting 100%, 99%, 98% and 97% highest peak heating demand for the 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario.

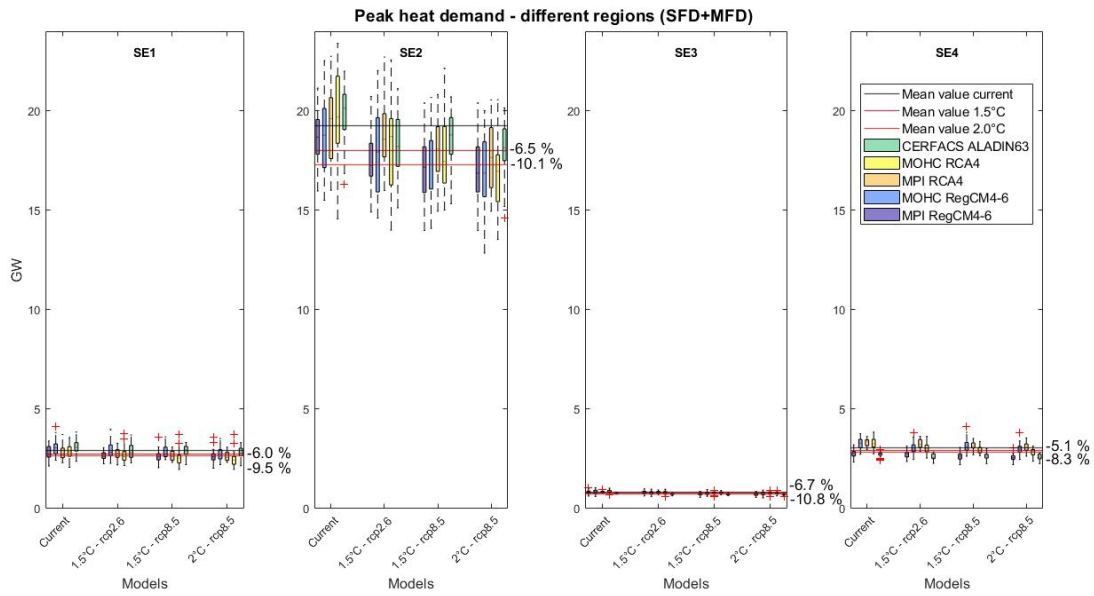


Figure 62: Yearly peak heating demand in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

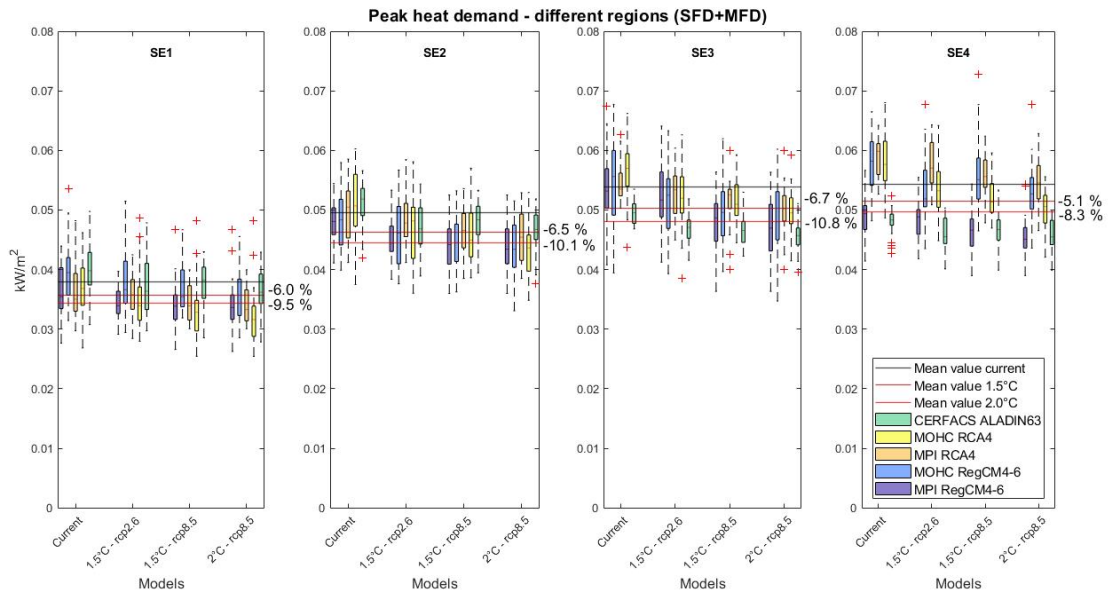


Figure 63: Yearly peak heating demand per heated floor area in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

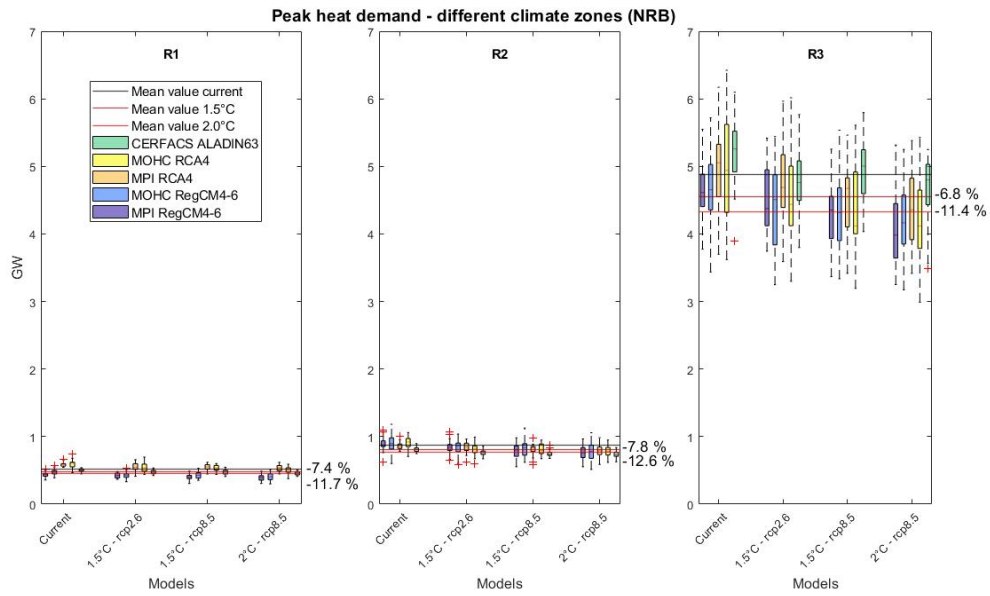


Figure 64: Yearly peak heating demand in the different regions R1, R2 and R3, only including NRB for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

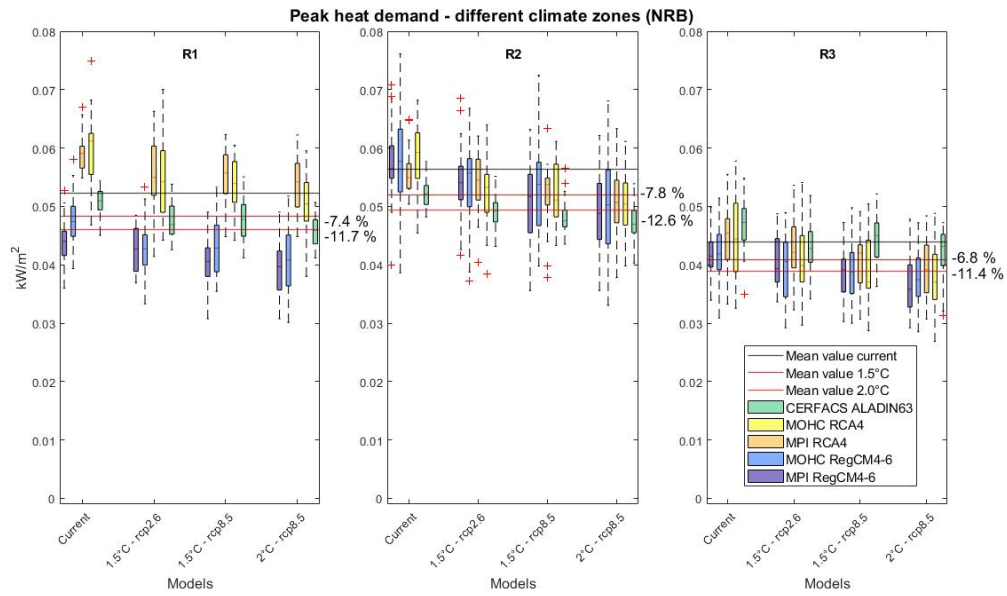


Figure 65: Peak heating demand per heated floor area in the different regions R1, R2 and R3, only including NRB for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

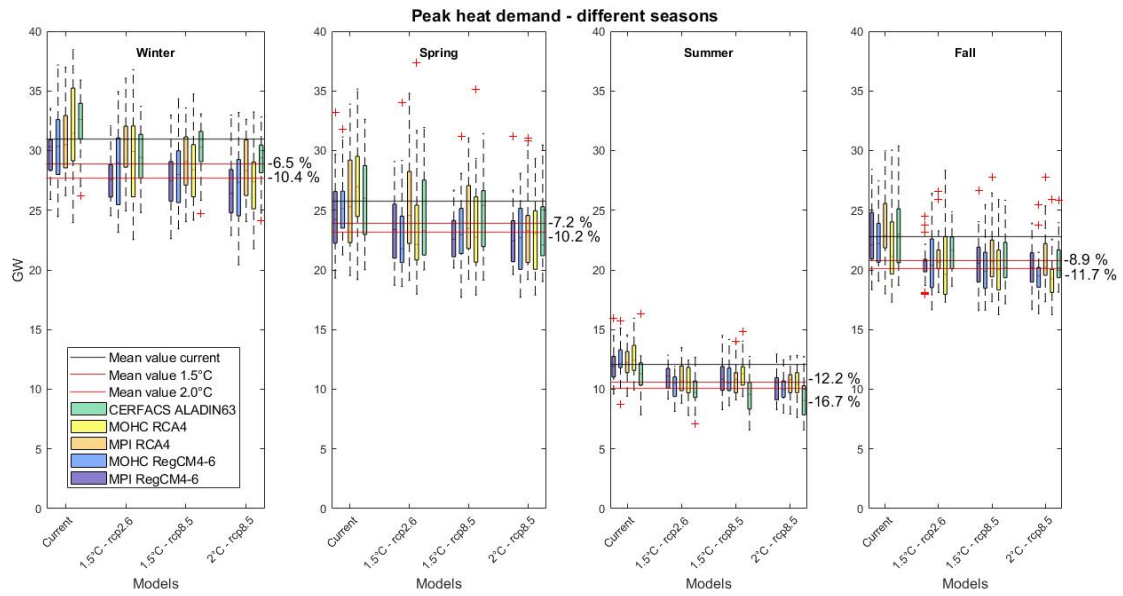


Figure 66: Peak seasonal heating demand in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

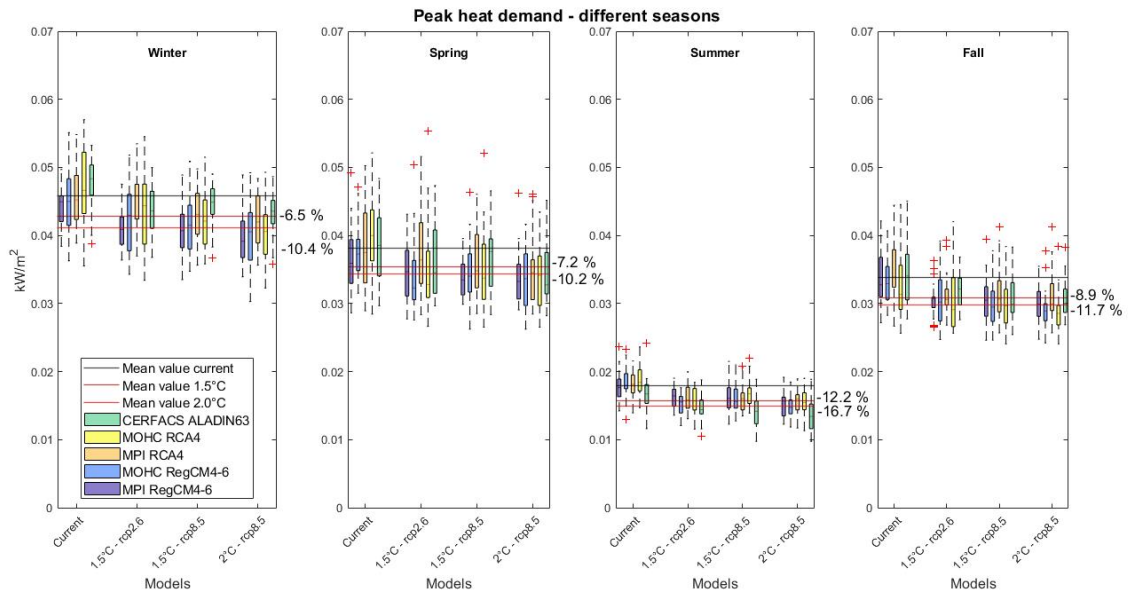


Figure 67: Peak seasonal heating demand per heated floor area in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

A.8. Peak cooling demand excluding ventilation through windows

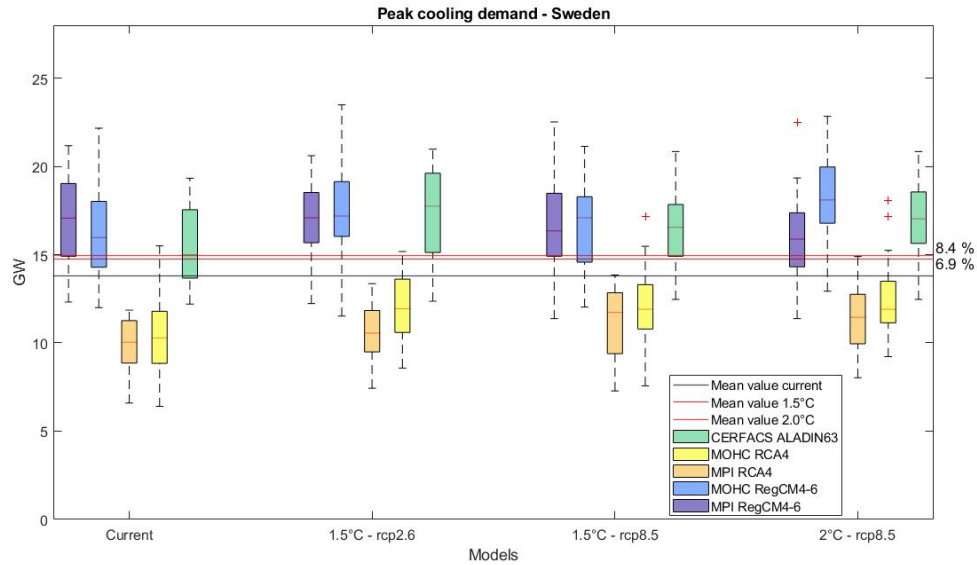


Figure 68: Yearly peak cooling demand in the Swedish building stock excluding ventilation through windows, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

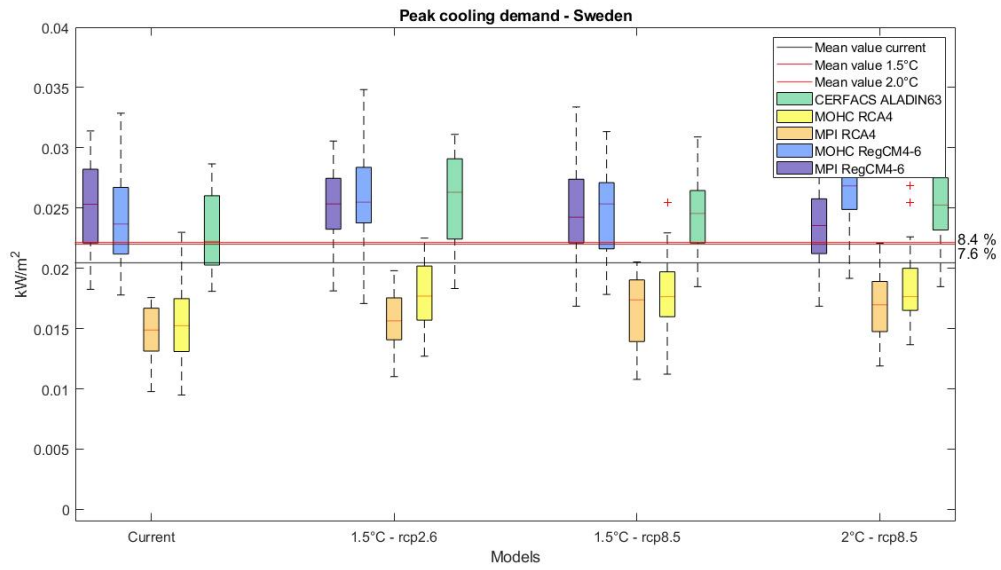


Figure 69: Yearly peak cooling demand in the Swedish building stock per heated floor area excluding ventilation through windows, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

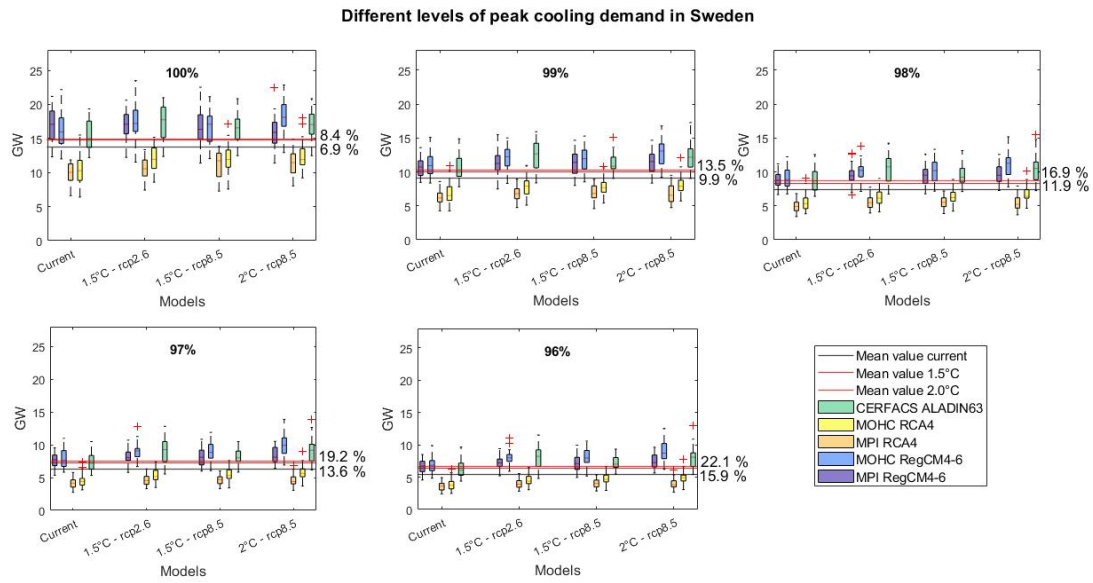


Figure 70: 4% of the yearly highest peak cooling demand in the Swedish building stock when excluding ventilation through windows. The different plots show how the climate is affecting 100%, 99%, 98% and 97% highest peak cooling demand for the 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario.

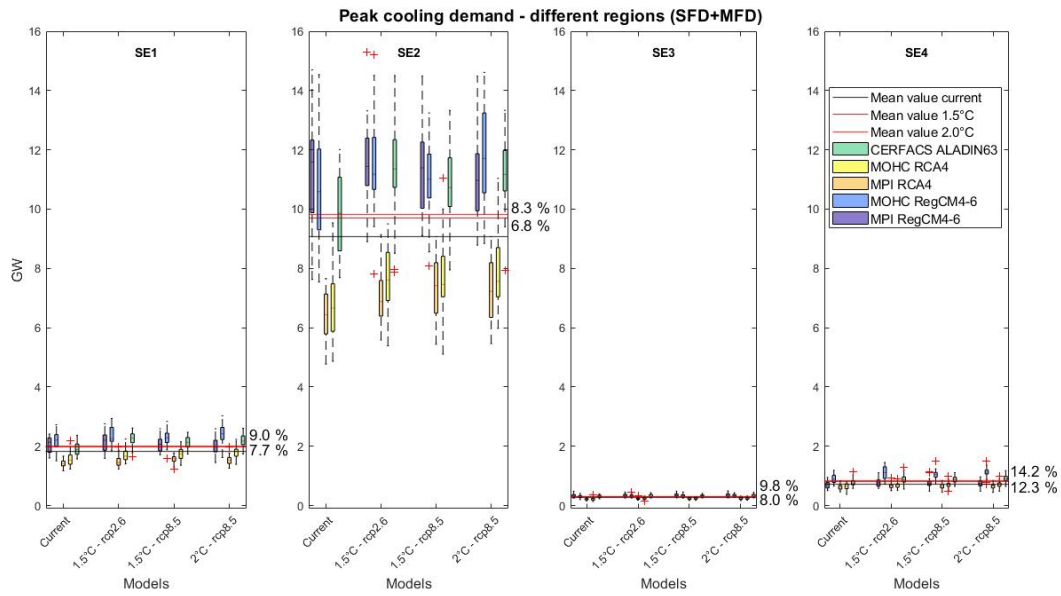


Figure 71: Yearly peak cooling demand in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD and excluding ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

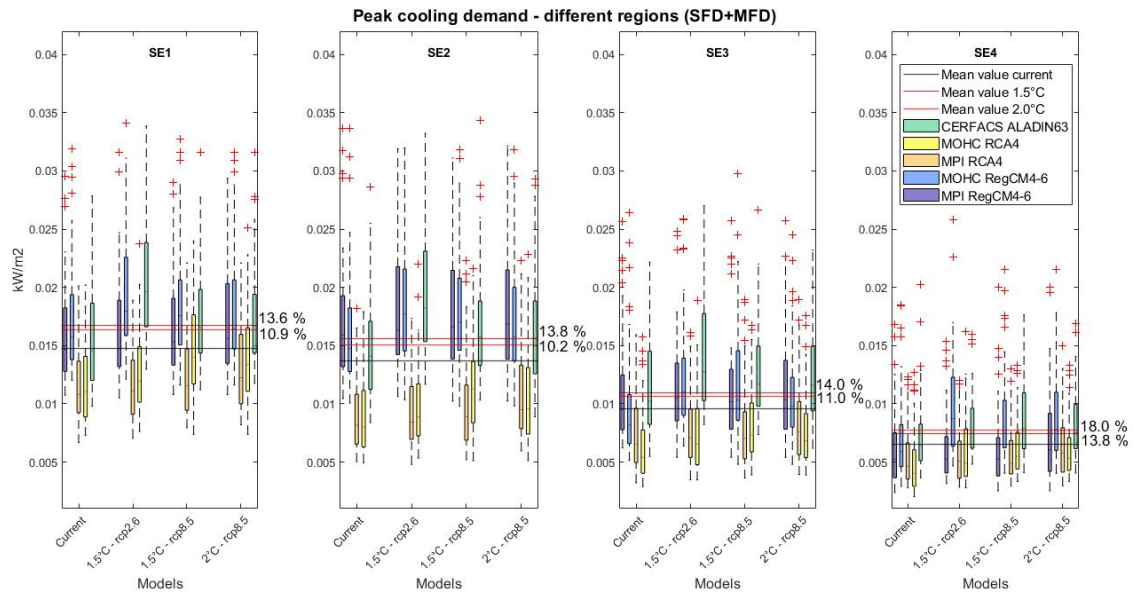


Figure 72: Yearly peak cooling demand per heated floor area in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD and excluding ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

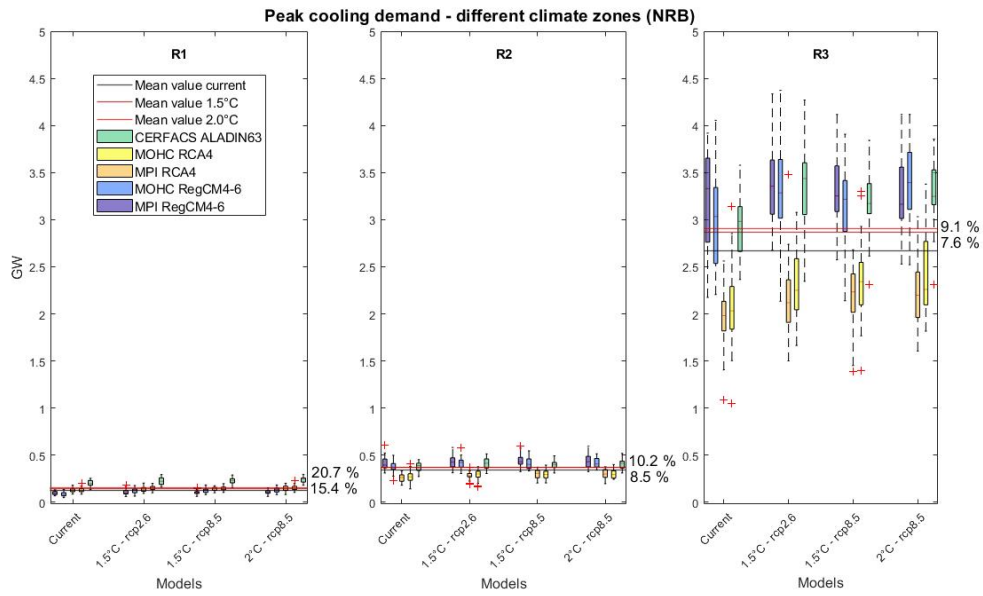


Figure 73: Yearly peak cooling demand in the different regions R1, R2 and R3, only including NRB and excluding ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

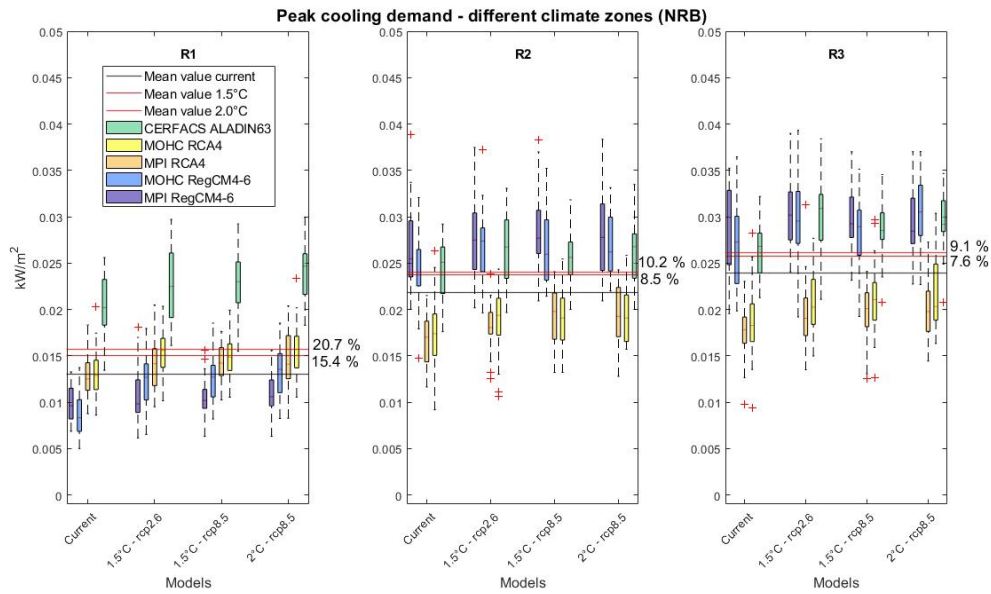


Figure 74: Yearly peak cooling demand per heated floor area in the different regions R1, R2 and R3, only including NRB and excluding ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

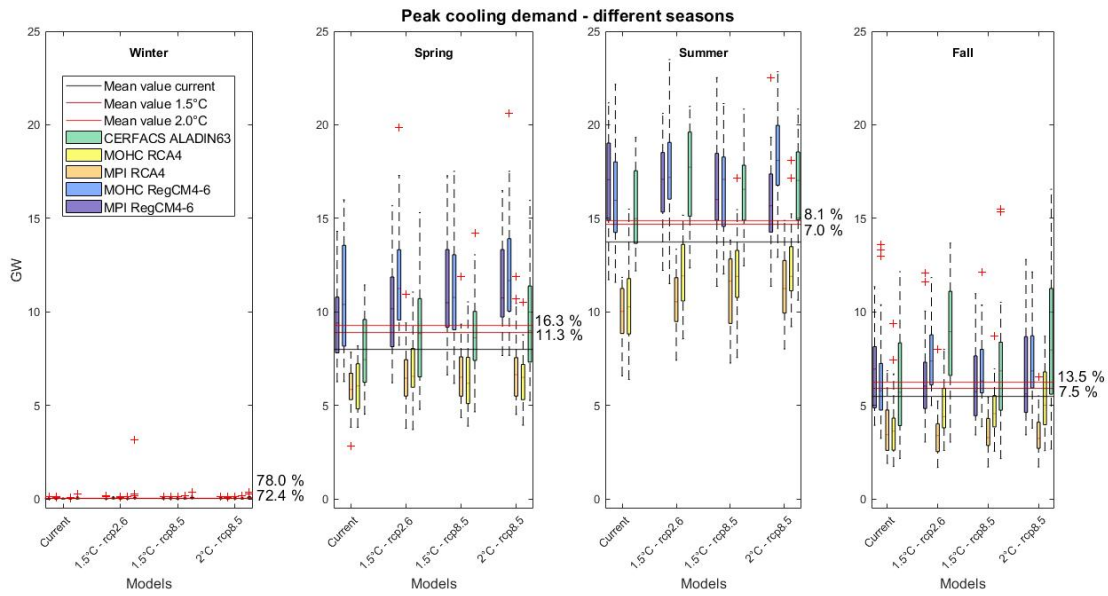


Figure 75: Peak seasonal cooling demand in the winter, spring, summer and fall season, when excluding ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

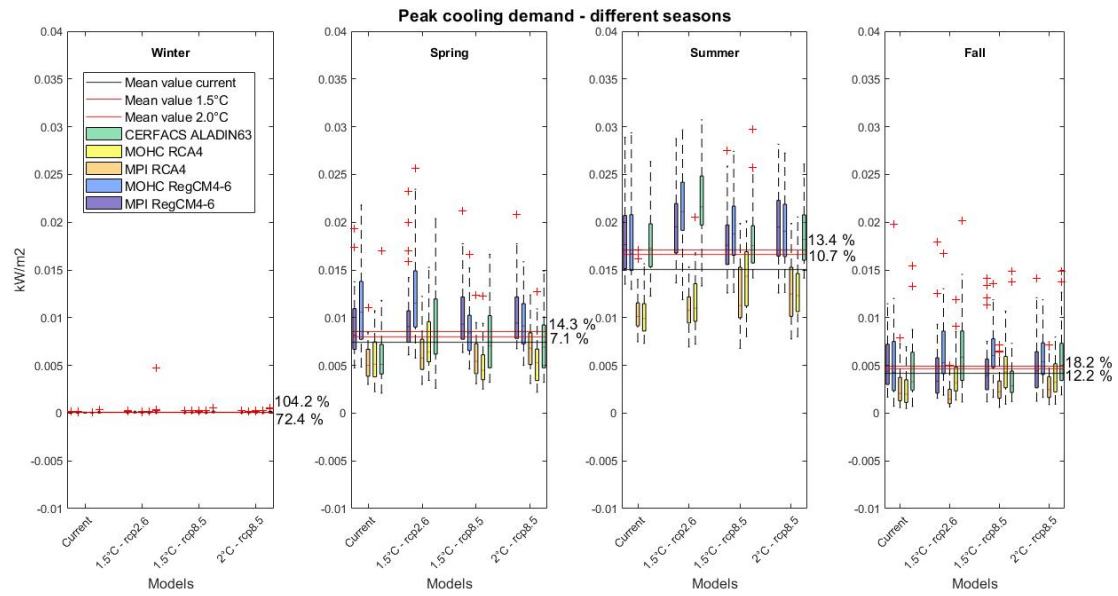


Figure 76: Peak seasonal cooling demand per heated floor area in the winter, spring, summer and fall season, when excluding ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

A.9. Peak cooling demand including ventilation through windows

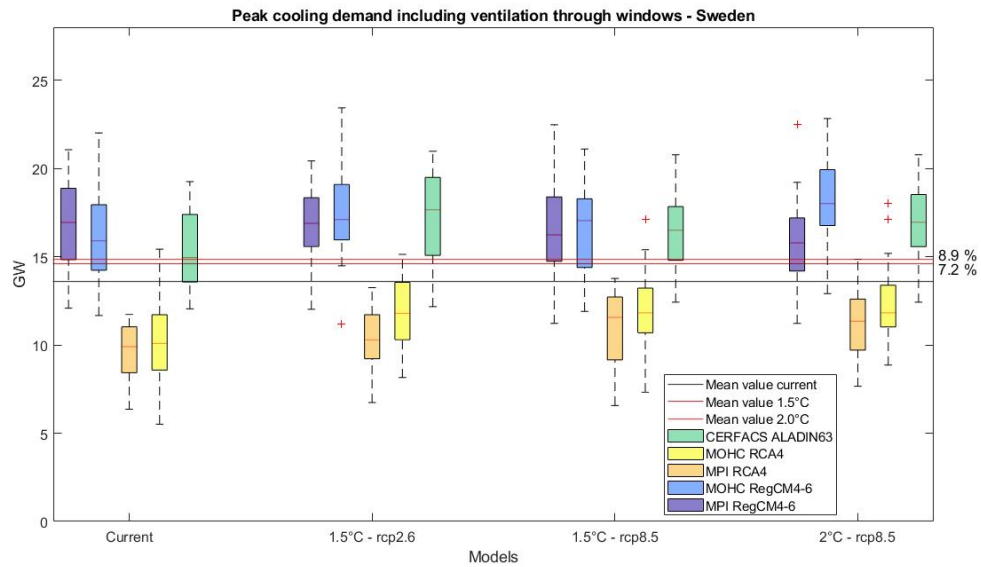


Figure 77: Yearly peak cooling demand in the Swedish building stock including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

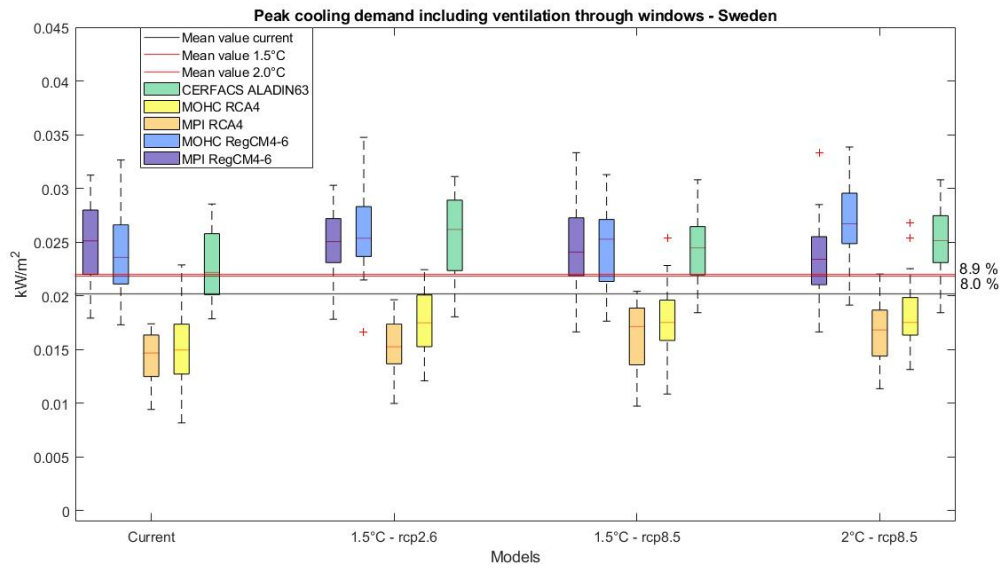


Figure 78: Yearly peak cooling demand in the Swedish building stock per heated floor area including ventilation through windows for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

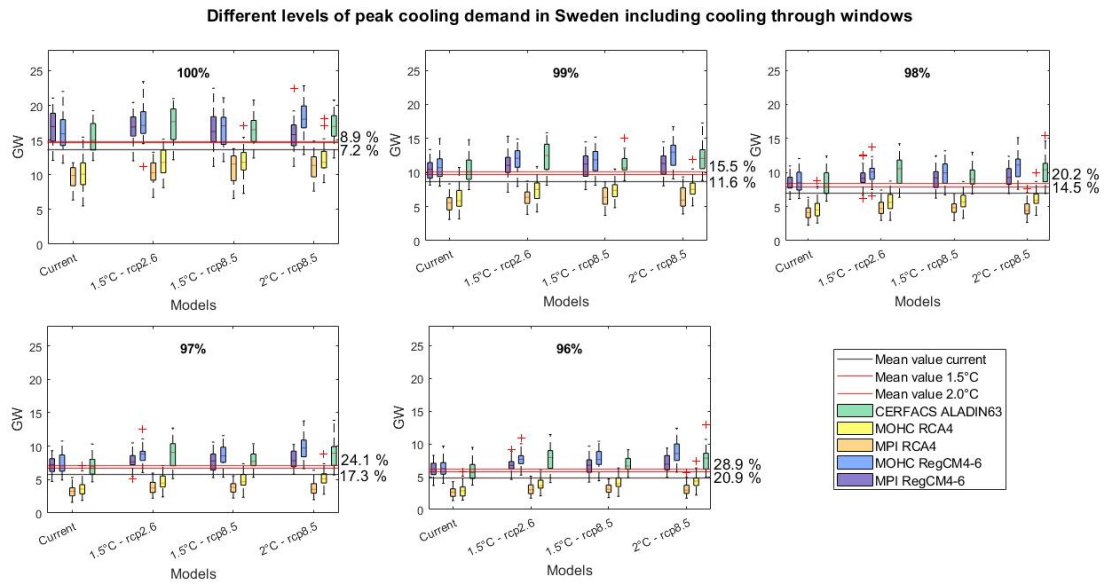


Figure 79: 4% of the yearly highest peak cooling demand in the Swedish building stock when including ventilation through windows. The different plots show how the climate is affecting 100%, 99%, 98% and 97% highest peak cooling demand for the 1.5°C – RCP 2.6, 1.5°C – RCP 8.6 and 2°C – RCP 8.6 climate scenario.

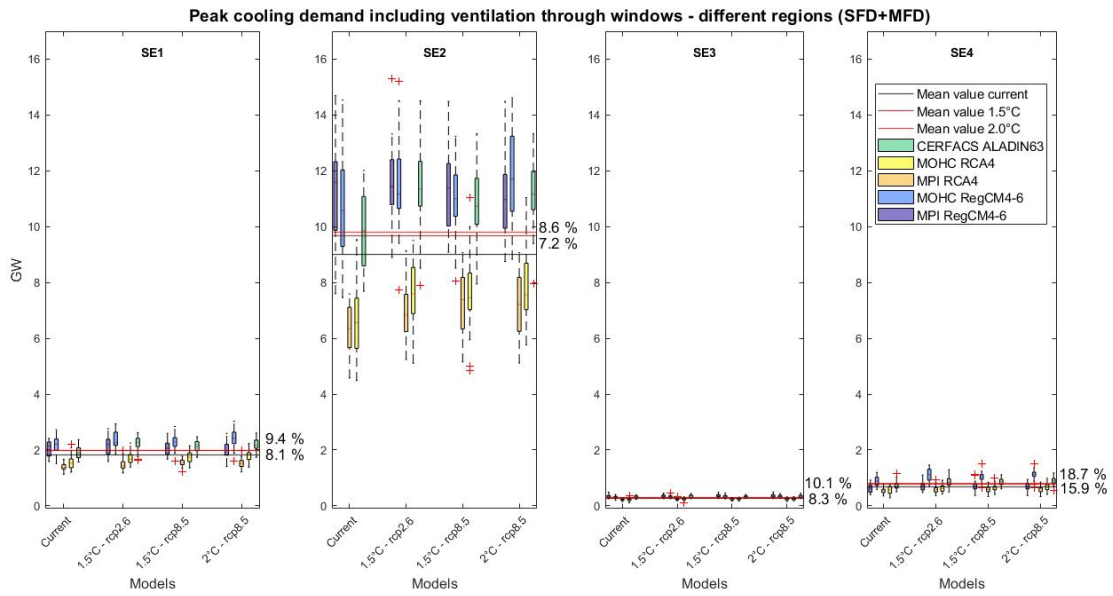


Figure 80: Yearly peak cooling demand including ventilation through windows in the different regions SE1, SE2, SE3 and SE4, only including SFD and MFD for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

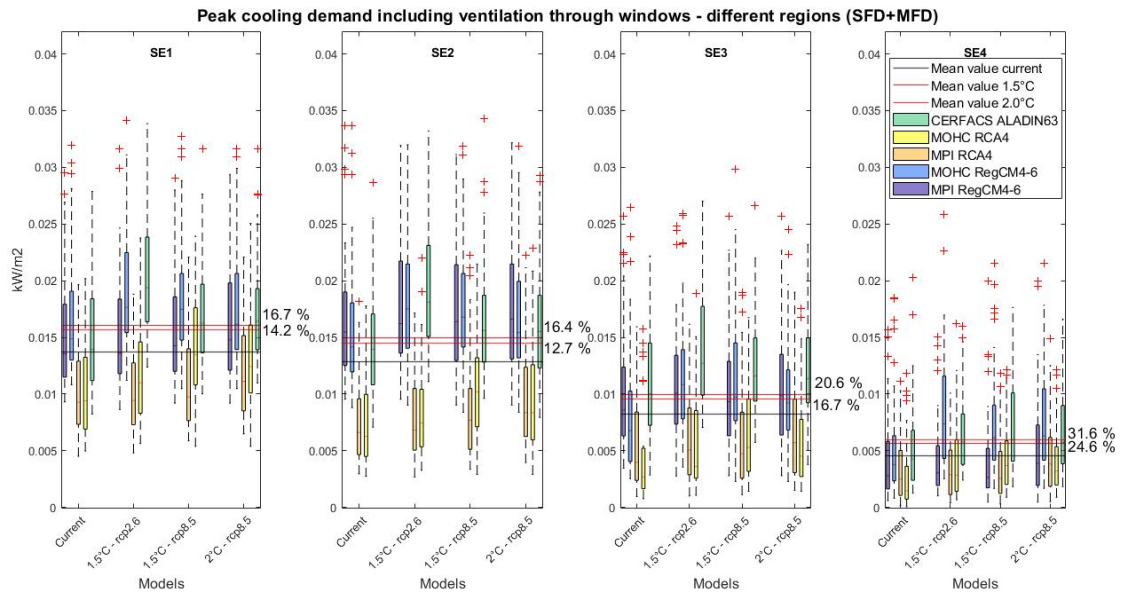


Figure 81: Yearly peak cooling demand per heated floor area including ventilation through windows in the different regions SE1, SE2 SE3 and SE4, only including SFD and MFD for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

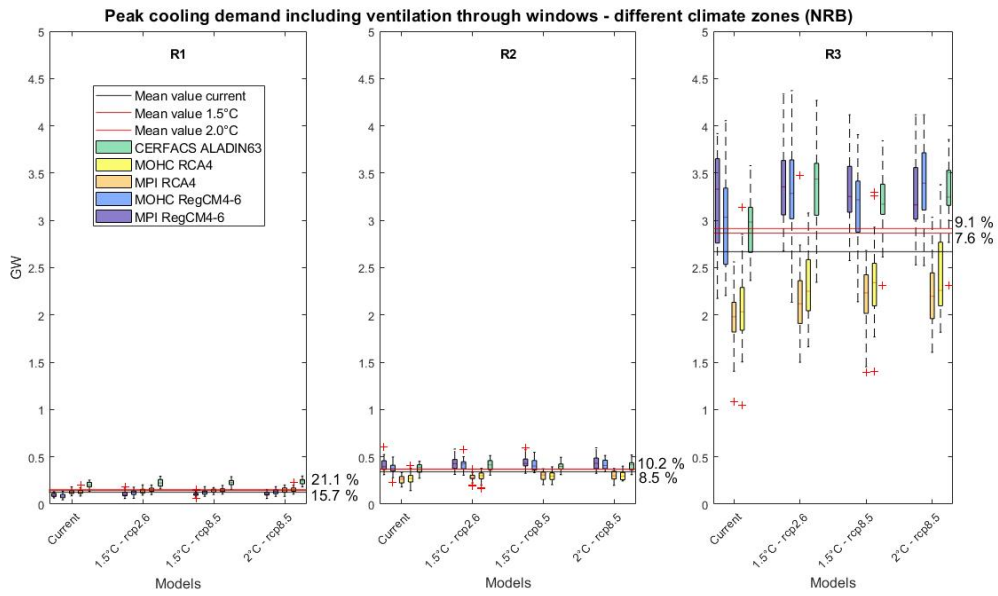


Figure 82: Yearly peak cooling demand including ventilation through windows in the different regions R1, R2 and R3, only including NRB for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

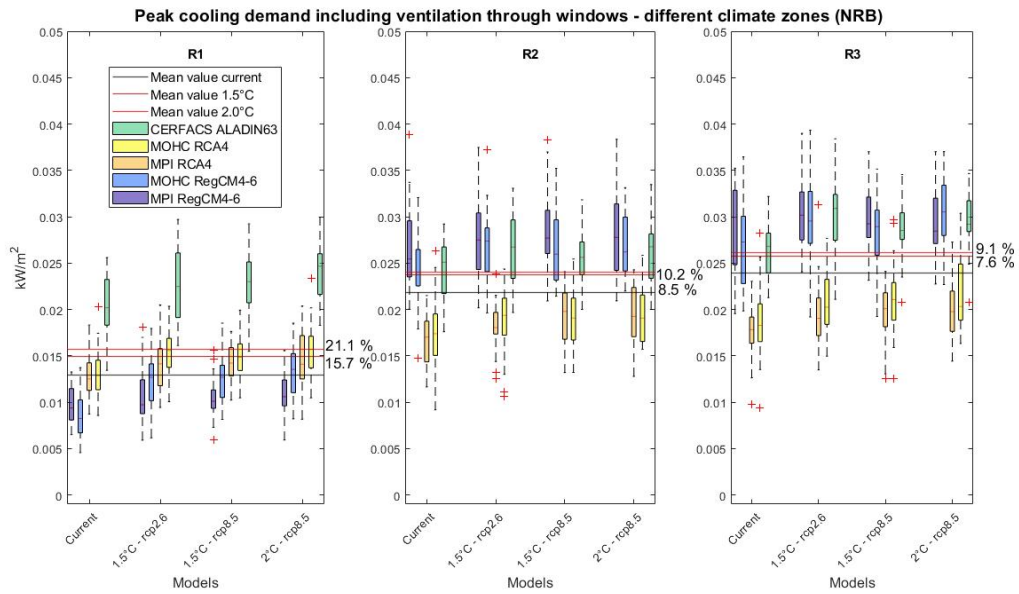


Figure 83: Peak cooling demand per heated floor area including ventilation through windows in the different regions R1, R2 and R3, only including NRB for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

A.10. Peak cooling demand per season including ventilation through windows

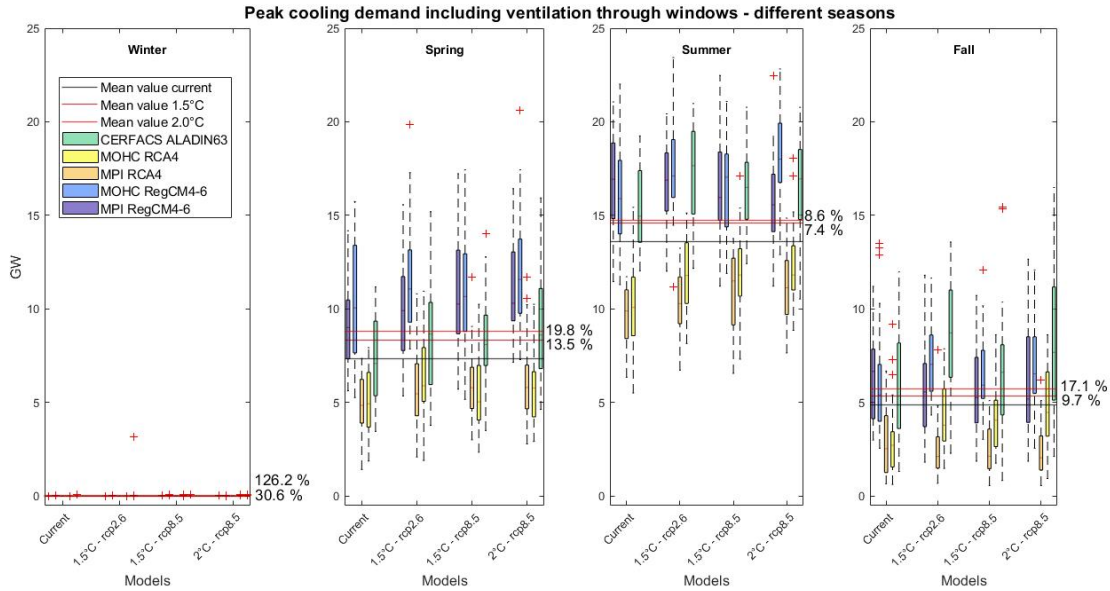


Figure 84: Peak seasonal cooling demand including ventilation through windows in the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

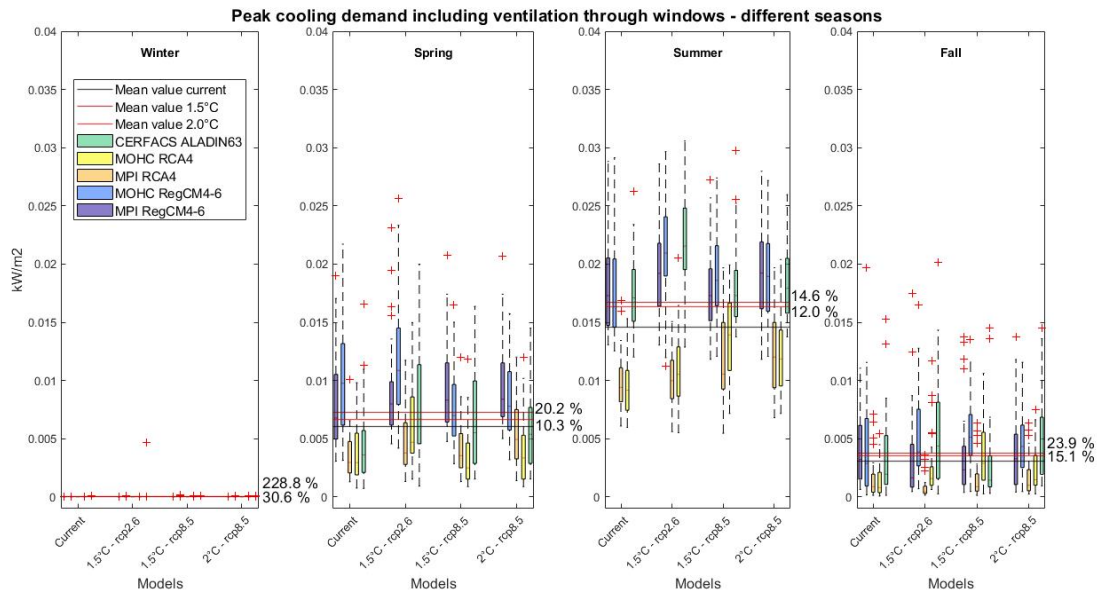


Figure 85: Peak seasonal cooling demand per heated floor area including ventilation through windows for the winter, spring, summer and fall season, for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average demand in the current scenario, the dark red line is the average demand in the 1.5°C scenario and the light red line is the demand in the 2°C scenario.

A.11. Heating period

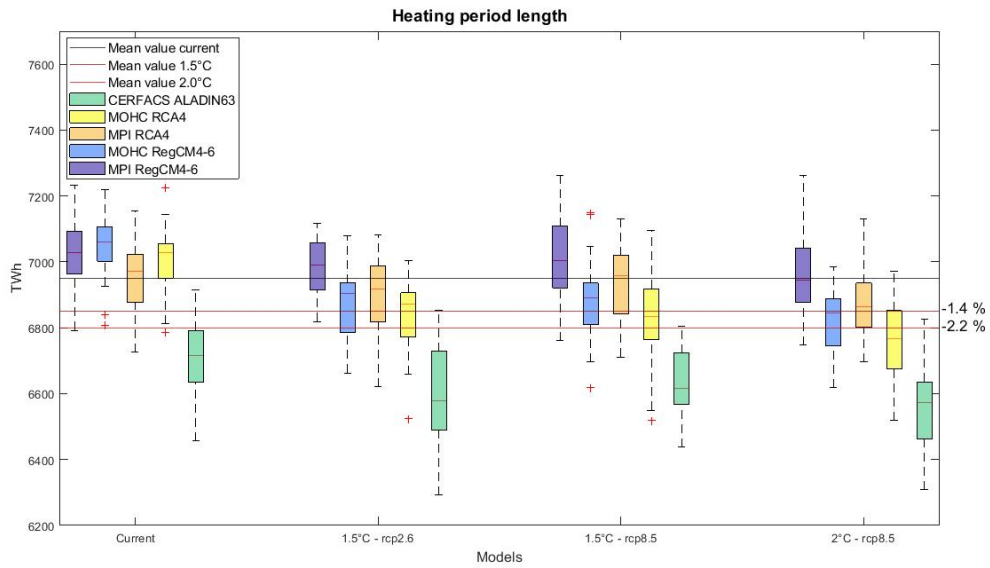


Figure 86: Heating period for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario. The black horizontal line marks the average length of the heating period in the current scenario, the dark red line is the average length in the 1.5°C scenario and the light red line is the average length in the 2°C scenario. (Note that the y-axis does not start at 0)

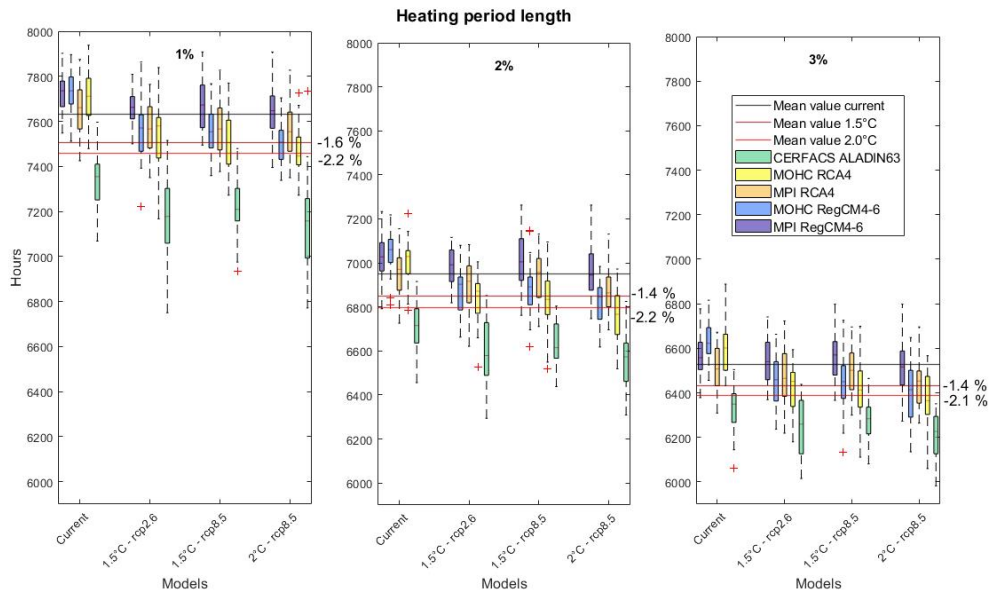


Figure 87: Heating period for the different climate models and the current, 1.5°C - RCP 2.6, 1.5°C - RCP 8.6 and 2°C - RCP 8.6 climate scenario at three different definitions of start and end points, 1%, 2% and 3%. The black horizontal line marks the average length of the heating period in the current scenario, the dark red line is the average length in the 1.5°C scenario and the light red line is the average length in the 2°C scenario. (Note that the y-axis does not start at 0)

B. Difference between models

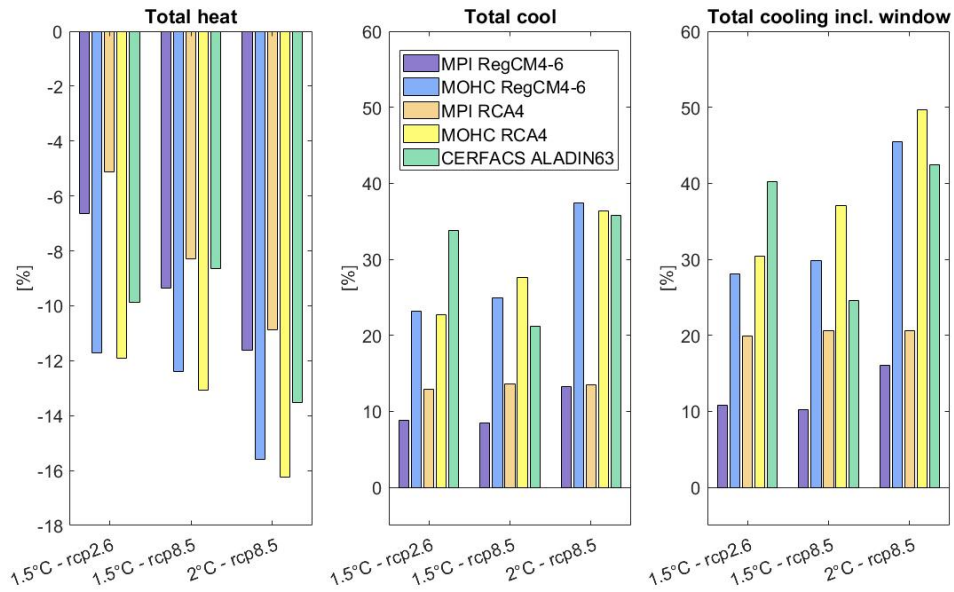


Figure 88: The degree of changed demand for the different models compared to the current demand for each model. The first box is the total heat demand, the second is the cooling demand and the last box is the cooling demand including ventilation through windows. The first scenario in every box is the demand at a global temperature increase of 1.5°C in the RCP 2.6 scenario, the second is 1.5°C temperature increase at RCP 8.5 and the last is 2°C temperature increase at RCP 8.5.

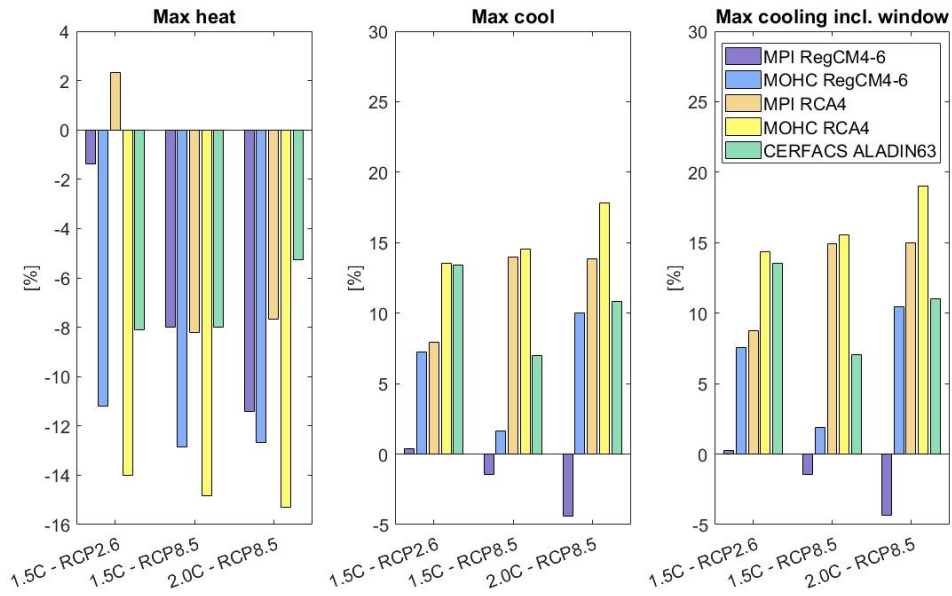


Figure 89: The degree of changed maximum effect for the different models compared to the current maximum effect for each model. The first box is the maximum heat effect, the second is the maximum cooling effect and the last box is the maximum cooling effect including ventilation through windows. The first scenario in every box is the maximum effect at a global temperature increase of 1.5°C in the RCP 2.6 scenario, the second is 1.5°C temperature increase at RCP 8.5 and the last is 2°C temperature increase at RCP 8.5.