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Original research article

Bespoke climate indicators for the Swedish energy sector – a stakeholder focused approach

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ABSTRACT

Climate change concerns the energy sector to a high degree because the sector is sensitive both to changing conditions for power and heat production, and to changing demand for electricity, heating and cooling. In this study potential consequences of climate change on different parts of the Swedish energy sector were assessed in a series of workshops, where climate and energy scientists, energy systems experts and analysts met with representatives of the energy sector to assess the vulnerability of the sector and consider what climate indicators could be used to assess impacts of relevance.

The impact of climate change depends on the energy type. Hydropower, for which production is naturally linked to weather and climate, is significantly impacted by climate change. For other forms of production, such as nuclear power, other factors such as e.g. policy and technology development are more important. The series of workshops held in this study, where different aspects of climate change and consequences were discussed, proved very successful and has increased our understanding of climate impacts on the energy system.

Practical implications

In this study climate researchers teamed up with energy scientists, energy systems experts, analysts and representatives of the Swedish energy sector to investigate how the sector will be affected by climate change. We know that the climate is changing and will continue to do so, which will impact the whole of society. Even though large quantities of climate data are available, they will not be useful unless they are translated into a form that is relevant for the sector in question which is preparing to take climate adaptation measures. It is also important to ensure that use is being made of the relevant data. This cannot be done by climate experts alone, but must be done together with sectoral representatives.

The central part of this study was a series of workshops where scientists, experts and sectoral representatives met. First the climate scientists, on the basis of a large ensemble of high-resolution regional climate models, showed projections of climate change, and explained the limitations and advantages of climate model data. Then representatives of the energy sector explained what climatic variables or weather events the sector is dependent on or sensitive to, as well as how these climate factors affect it. Thereafter, on the basis of the requirements expressed by the sector, the climate scientists defined climate indicators that could help to describe the potential consequences of climate change on the different parts of the energy sector.

As an example, for wind power generation, the average wind speed is important for the production potential, and the number of calm and

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stormy days affect the operations. Furthermore, icing of rotor blades is the largest maintenance problem experienced by the sector. Consequently, the climate scientists analysed wind speed and calculated the number of calm and stormy days. Icing of rotor blades could not be studied directly. Instead, a few indicators were identified that could serve as proxies for conditions favourable for icing: e.g. number of days with zero crossings (i.e., with minimum temperature below zero degrees Celsius and maximum temperature above zero), or number of days when the temperature was close to zero degrees and precipitation occurred. All changes in indicators related to wind were judged to be uncertain, but the consequences of these changes, if they were to occur, were judged to be large. Positive consequences from an energy system perspective are increased mean wind speed; negative ones are decreased wind speed and more storms. The prevalence of conditions favourable for icing on rotor blades will change in a warmer climate, but the effect varies between regions of the country. In southern Sweden a warmer climate would lead to fewer problems with icing, while in the north it could lead to more problems in winter. This means that incidence of icing moves north and generally becomes less of a problem for the sector as a whole, even though the local variations are large. It was also clear from the dialogue at the workshops that not all variables important for generating relevant climate indicators are saved from climate models by default. Wind speeds at heights relevant for wind power (100—300 m) are not standard output variables in most climate models.

It is uncertain what level of global warming will be reached in the next decades. This study shows that it is a viable approach to work with global warming levels instead of defined time periods when analysing climate change impacts on the energy system. This shifts the focus from a specific period in time, for which the extent of climate change is uncertain, to a level of climate change that will most likely occur at some point in the future. Both + 1.5 °C and + 2 °C global warming levels will be reached within the 21st century unless greenhouse gas emissions are drastically reduced, which corresponds to the time horizon of investments for a typical power plant. Still, a limited set of models, such as that used in this study, run over a limited number of years can never catch the full variability of the climate, and another set of models would give different results. As the results are sensitive to the exact ensemble of climate models used, we have chosen to give qualitative statements about the projected changes instead of exact numbers. We argue that this level of detail is enough to highlight plausible impacts on the energy system.

In general, an assessment of the combined effect of climate change on the energy system requires knowledge about both the energy system and the climate of the future, and thus requires cross-sectoral and/or interdisciplinary cooperation. The development of the energy system is governed both by factors that are relatively well known and factors that are associated with large uncertainties. The future energy system in Sweden and northern Europe may be characterized by a much larger share of renewable energy, mainly wind power, than today. Knowledge about the impact of climate change on the different energy sub-sectors and sources is thus of large importance in a systems perspective.

Weather and climate related factors already have an impact on the energy system to some extent today. For example, several of the most common causes of short duration power outages are directly or indirectly weather related. Annual hydropower production varies between dry and wet years, and energy demand is affected by e.g. temperature and radiation. Climate change brings different consequences on the energy system – increased risks and changed conditions but also new opportunities, such as an increased potential for hydropower production due to increased precipitation and possibly increased supply of forest biomass for biofuels in e.g. the Nordic region due to e.g., increased temperature (resulting in a longer growing season).

1. Introduction

The global climate is changing rapidly and will bring profound global consequences (IPCC, 2021; IPCC, 2022a). For Sweden and northern Europe, the projected temperature increase is strong and considerably larger than the global average (Kjellström et al., 2022). For example, observed changes include both shorter and milder winters and longer and warmer summer seasons as well as increasing levels of precipitation and changes to the hydrological cycle. Consequences of these changes concern the energy sector because it is sensitive both to changing conditions for power production and heat production (e.g. centralized in the form of district heating, in Sweden to a large extent based on biomass), as well as to changing demand for electricity, heating and cooling. The much warmer winters in Sweden over recent decades have already resulted in a marked decrease in the heating degree days (SMHI, 2021). In summer, a corresponding, albeit much smaller, increase in the number of degree days for cooling has been observed. Another consequence related to hydrology is the observed trend of an earlier spring flood due to the shorter snow season in Scandinavia resulting from the higher temperatures (Arheimer and Lindström, 2015; Matti et al., 2017; Scharff, 2023).

The magnitude of future climate change depends mostly on the future amount of greenhouse gas emissions (IPCC, 2021). The time perspective is also important, and the energy sector is expected to be impacted progressively more strongly by a warmer climate (Dodman et al., 2022; Bednar-Friedl et al., 2022). In addition to changes in supply and demand of energy, the vulnerability of the energy system is impacted by changes in weather and climate related extremes. Examples include changes in streamflow and risk of high flows (Arheimer and Lindström, 2015) and changes in drought and forest fires (Venäläinen et al., 2020; Krikken et al., 2021; Patacca et al., 2022). These, and other types of climate related changes pose new challenges for the energy sector in addition to its vital role in the transition to a society with radically reduced use of fossil fuel (IPCC, 2022b).

The energy system is to a very high degree connected to the climate system. The conditions for power production and heat production (e.g. district heating from biomass in separate plants) are affected by climate, especially when a larger proportion of the electricity and heat originates from renewable sources (Reckermann et al., 2022). It is also clear that other factors than climate affect the energy system. An example is the hydropower regulation of rivers that in some cases dominates over climate change impacts (e.g. Arheimer et al., 2017).

Earlier assessments of impacts of climate change on energy systems in the Nordic countries include Fenger (2007) addressing renewable energy sources; Kjellström et al. (2011) addressing impacts, risks and adaptation; and, focussing on Sweden, Gode et al. (2007). Common to these assessments is that they are based on a small number of regional climate model (RCM) projections driven by a few global climate models. This implies that they represent only a limited part of the spread in larger model ensembles such as those generated in the *Coupled Model Intercomparison Projects* (CMIP5, Taylor et al., 2012; CMIP6, Eyring et al., 2016) or the *Coordinated Regional climate Downscaling Experiment* (CORDEX, Jones et al., 2011). Furthermore, these RCMs were run at coarser horizontal resolution (e.g. 50 km grid spacing) than today's RCMs such as those in EURO-CORDEX, where the standard resolution is 12.5 km for Europe (Jacob et al., 2014). Downscaling to higher resolution better describes important processes (e.g. low-pressure systems) and geographic characteristics (altitude, coastlines etc.). The higher resolution gives a more realistic description of the climate at regional and local spatial scales (e.g. Torma et al., 2015; Prein et al., 2016) and allows for better representation of temporal variability such as that associated with short duration intense rainfall (Olsson et al., 2015). The point of using a large number of RCM simulations, based on several models, is that the robustness of the calculated changes can be assessed (e.g. Christensen and Kjellström, 2020; 2021). Strong agreement between models points to a robust result, whereas large spread points to larger uncertainty. Studies based on RCMs and RCP scenarios show that the potential hydropower production is projected to increase in northern Europe and decrease in southern Europe (Lehner et al., 2005; Mima et al., 2025; Tobin et al., 2018). Projections for wind energy potential are uncertain. Some studies give a general decrease across Europe (Carvalho et al., 2017; Davy et al., 2018; Tobin et al., 2018), while others at least see increased potential in northern or northwestern Europe (Devis et al., 2018; Hosting et al., 2018).The potential for photovoltaic production is projected to decrease generally in Europe, with the largest decrease in the Scandinavian and Baltic countries (Jerez et al., 2015; Tobin et al., 2018). The effect of climate change on bioenergy has received little attention (Solaun and Cerdá, 2019).

This study focusses on the energy sector in Sweden and how it may be impacted by future climate change. Both impacts on power production and heat production were included. Electricity production in Sweden amounted to 168 TWh in 2021 and was based on hydropower (73 TWh), nuclear power (51 TWh), wind power (27 TWh) and combined heat and power (15 TWh). There was also a very small amount of solar power production (1 TWh). Heat demand in the residential and services sector was 80 TWh in 2021, and was met by district heating (47 TWh), electricity based heat solutions (22 TWh), individual biomass boilers (10 TWh) and individual fossil fuel boilers (2 TWh). The district heating production in Sweden is mainly based on biomass and waste, industrial waste heat and electricity. Based on the Swedish power and heat production system, the following areas were selected for analysis of climate consequences: hydropower, wind power, nuclear power, electricity grids, district heating and bioenergy.

Potential consequences of climate change were assessed in a series of workshops, where climate and energy scientists, energy systems experts and analysts met with representatives of the energy sector to discuss the vulnerability of the sector and consider what climate indicators could be used to assess impacts of relevance for the energy sector. These workshops also resulted in recommendations for the different sub-sectors. The expected development of the Swedish energy system in terms of production of power and district heating was used as basis for the assessment and for the selection of the energy sources included. Due to the expected increase in electricity demand (as in other Nordic and EU countries), wind power production is expected to increase considerably in Sweden (Swedish Energy Agency, 2023). Biomass based district

Table 1
Model simulations assessed. Details about GCMs are found in Taylor et al. (2012), details about the RCMs are found in Vautard et al. (2020). The timing of the global warming levels (GWL) are calculated for RCP8.5, and when possible for RCP4.5 (the latter given in brackets).

Driving GCM		Timing of		RCM	Scenario	
GCM	No.	GWL1.5	GWL2		RCP4.5	RCP8.5
CCCma-CanESM2	r1i1p1	1999–2028	2012–2041	CLMcom-CCLM4-8–17	–	X
	r1i1p1			GERICS-REMO2015	–	X
CNRM-CERFACS-CNRM-CM5	r1i1p1	2015–2044	2029–2058	CNRM-ALADIN63	–	X
	r1i1p1			DMI-HIRHAM5	–	X
	r1i1p1			IPSL-WRF381P	–	X
	r1i1p1			KNMI-RACMO22E	–	X
ICHEC-EC-EARTH	r1i1p1	2003–2032	2021–2050	DMI-HIRHAM5	–	X
	r1i1p1	(2006–2035)	(2028–2057)	KNMI-RACMO22E	X	X
	r1i1p1			SMHI-RCA4	.	X
	r3i1p1	2006–2035	2023–2052	DMI-HIRHAM5	X	X
	r3i1p1	(2009–2038)	(2030–2059)	KNMI-RACMO22E	.	X
	r3i1p1			SMHI-RCA4	.	X
	r12i1p1	2005–2034	2021–2050	CLMcom-CCLM4-8–17	X	X
	r12i1p1	(2010–2039)	(2031–2060)	CLMcom-ETH-COSMO-crCLIM-v1-1	–	X
	r12i1p1			DMI-HIRHAM5	–	X
	r12i1p1			GERICS-REMO2015	–	X
	r12i1p1			KNMI-RACMO22E	X	X
	r12i1p1			SMHI-RCA	X	X
IPSL-IPSL-CM5A-MR	r1i1p1	2002–2031	2016–2045	IPSL-INERIS-WRF331F	X	X
	r1i1p1	(2002–2031)	(2020–2049)	IPSL-WRF381P	–	X
	r1i1p1			KNMI-RACMO22E	–	X
	r1i1p1			SMHI-RCA4	X	X
MIROC-MIROC5	r1i1p1	2019–2048	2034–2063	CLMcom-CCLM4-8–17	–	X
	r1i1p1			GERICS-REMO2015	–	X
MOHC-HadGEM2-ES	r1i1p1	2010–2039	2023–2052	CLMcom-CCLM4-8–17	X	X
	r1i1p1	(2016–2045)	(2032–2061)	CNRM-ALADIN63	–	X
	r1i1p1			DMI-HIRHAM5	–	X
	r1i1p1			GERICS-REMO2015	–	X
	r1i1p1			IPSL-WRF381P	–	X
	r1i1p1			KNMI-RACMO22E	X	X
	r1i1p1			SMHI-RCA4	X	X
	r1i1p1			UHOH-WRF361H	–	X
MPI-M-MPI-ESM-LR	r1i1p1	2004–2033	2021–2050	CLMcom-CCLM4-8–17	X	X
	r1i1p1	(2006–2035)	(2029–2058)	CLMcom-ETH-COSMO-crCLIM-v1-1	–	X
	r1i1p1			KNMI-RACMO22E	–	X
	r1i1p1			MPI-CSC-REMO2009	X	X
	r1i1p1			SMHI-RCA4	X	X
	r1i1p1			UHOH-WRF361H	–	X
	r2i1p1	2002–2031	2018–2047	CLMcom-ETH-COSMO-crCLIM-v1-1	–	X
	r2i1p1	(2004–2033)	(2026–2055)	MPI-CSC-REMO2009	X	X
	r2i1p1			SMHI-RCA4	–	X
	r3i1p1	2006–2035	2020–2049	CLMcom-ETH-COSMO-crCLIM-v1-1	–	X
	r3i1p1			GERICS-REMO2015	–	X
	r3i1p1			SMHI-RCA4	–	X
NCC-NorESM1-M	r1i1p1	2019–2048	2034–2063	CLMcom-ETH-COSMO-crCLIM-v1-1	–	X
	r1i1p1	(2027–2056)	(2062–2091)	DMI-HIRHAM5	X	X
	r1i1p1			GERICS-REMO2015	–	X
	r1i1p1			IPSL-WRF381P	–	X
	r1i1p1			KNMI-RACMO22E	–	X
	r1i1p1			SMHI-RCA4	X	X

heating represents 66 % of the district heating production, followed by other fuels and waste heat and the share of renewable energy in the district heating sector is expected to increase further (Swedish Energy Agency, 2023).

Based on the most recent large ensemble of EURO-CORDEX regional climate model projections, we address potential impacts on the energy sector in Sweden. To facilitate comparison and to focus on near- and mid-term changes we assess global warming periods when the annual global mean surface temperature (GMST) reaches 1.5 °C and 2 °C above pre-industrial levels.

2. Method and data

2.1. Climate models

The information about projected climate change is based on results from a large number of RCM simulations from EURO-CORDEX (Jacob et al., 2014), performed on 12.5 × 12.5 km horizontal grid spacing for the whole of Europe. The seven RCMs operated in different versions are forced with data from different ensemble members run by eight global climate models (GCMs) at resolutions of 50–200 km (Table 1).

RCM simulations downscaling ERA-Interim reanalysis data (Dee et al., 2011) are first used to evaluate the RCMs, because the GCM-driven results cannot be compared directly to observations. When comparing temperature and precipitation, the models are in general in good agreement with observations (the E-OBS17 0.22° data set as well as national data sets for precipitation interpolated to a common grid). Next, 66 RCM simulations with RCMs downscaling CMIP5 GCMs are assessed. It was not possible to use the full set of EURO-CORDEX RCMs for all variables since specific data from some models are missing. On a European level many of the EURO-CORDEX CMIP5-based RCM simulations used in this study have previously been assessed by Vautard et al. (2021) for the past climate and Coppola et al. (2021) for future climate change signals.

In an evaluation of 55 of the 66 RCM simulations used here, Vautard et al. (2020) showed that the RCMs in general agree well with observations and reanalyses. A number of systematic deviations was, however, identified: the RCMs are in general too cold, too wet and too windy. Another important result is that it is not possible to identify one single RCM that is always the "best" or "worse" for all criteria. This means that it is difficult to exclude simulations. That is one motivation for us to use an ensemble as large as possible. Another reason is that the larger number of simulations allows for better sampling uncertainties related to future climate change emanating from different GCM-RCM combinations (Christensen and Kjellström, 2020; 2021).

The RCMs used here are able to represent large parts of the variability of the climate system, at different spatial and temporal scales. Despite showing a clear improvement compared to previous material based on lower resolution (e.g. Kjellström et al., 2016), the RCMs still show biases compared to observations, implying that some climate indicators are difficult to interpret. Bias adjustment could potentially be a solution to this, but here it was not possible mainly due to the lack of sufficiently good observations of some of the variables of interest; especially variables related to wind, but also evaporation and radiation. In the cases where we had gridded observations covering the domain, we made rough estimates of how well the RCM-simulated climates compare to the observed climate. These estimates were made both for the ERA-Interim-driven and GCM-driven RCM simulations. Otherwise, we rely on previous evaluations of RCMs (e.g. Vautard et al., 2020). The information on the quality of the RCMs is part of our assessment of the certainty of the results, and what we can say about future climate change. Large uncertainties and errors in the RCMs' representations of specific variables reduce the confidence in statements about future climate change. On the other hand, the fact that the data are not bias adjusted means that all variables from one RCM are internally consistent. This is generally not necessarily the case for bias adjusted variables, that are commonly adjusted separately (e.g. Wilcke et al., 2013).

We handle model uncertainty by using all available simulations to maximize ensemble spread and by using warming levels to minimise the uncertainty associated with the timing. Still, a limited set of models, such as that used here, run over a limited number of years can never catch the full variability, and another set of models would give different results. In principle, the analysed material allows for quantitative estimates of changes projected by the RCMs to be made. Similarly, the spread can be used to assess the associated uncertainty. However, as the results are sensitive to the exact GCM-RCM combinations, we have chosen to give more qualitative statements about projected changes and their likelihood. Also, the large natural variability implies that the actual future evolution may differ from any of the assessed projections for periods of years to decades or even more (e.g. Deser et al., 2020). It could also be argued that, as impacts are local by their nature and as an exact configuration of the future energy system is not known, it is not meaningful to try to assess the full impacts with any precision.

2.2. Global warming levels

We have used data from two scenarios of future radiative forcing: RCP4.5 and RCP8.5 (Moss et al., 2010). To identify the time when a global warming level (GWL) is reached we have used the annual global mean surface temperature (GMST) in each GCM simulation. The period 1861–1890 is used as reference since this is the earliest period with data from all historical GCM simulations. The timing of a GWL is defined as the first 30-year period in which the 30-year mean of the GMST reaches the specified warming level compared to the mean of 1861–1890. In this way, different time periods from climate models with different radiative forcing and climate sensitivity can be compared since the global warming is by definition the same in all. The timing of a GWL depends on assumptions of radiative forcing, the climate sensitivity in the respective models and natural internal variability. Table 1 shows that the periods for + 1.5 °C (GWL1.5) and + 2 °C (GWL2) partly overlap. Further, we note that the GMST is changing through the 30-year periods, implying that the analysed periods are not descriptions of a stationary climate. This may have an impact on the interpretation of the results, especially when it comes to extreme events that may show different frequency or intensity at the beginning or end of a 30-year period, as a result of the warming trend (Bärring & Strandberg, 2018).

The climates of the GWLs are compared to the reference period 1971–2000. The choice of reference period is partly a consequence of data availability, because some simulations start at 1971, and partly because the reference period should end before 2005, when the scenarios start.

2.3. Calculation of indicators

Based on output from the RCMs, different climate indicators are calculated. A climate indicator can be standard variables output, such as temperature, precipitation, and humidity; or a value derived from these variables, such as the number of dry days, length of the vegetation period or cooling degree days. In some instances, we have also assessed indicators that are combinations of variables. The selection of indicators to be used was defined in dialogue with representatives from the energy sector, as outlined below. The indicators that were analysed are listed in Table 2.

2.4. Workshops and user dialogue

Six working groups (WGs) were set up, representing respectively: hydropower; wind power; nuclear power; bioenergy; electricity grid and energy use; and district heating and cooling. Each WG consisted of 10–15 participants from energy companies, authorities, sector organisations and researchers. Three workshops were held for each WG addressing how RCM data could be connected with the needs of the

Table 2
The indicators calculated within the project. Name, definition, unit, time period of aggregation (yearly (Y), seasonally (S), monthly (M)) and the number of simulations (N) used in the calculation of the indicator.

Abbreviation	Climate indicator	Unit	Time period (M/S/Y)	N
TAS	Diurnal mean temperature	°C	S/Y	66
TX	Daily maximum temperature	°C	M/S/Y	66
TN	Daily minimum temperature	°C	M/S/Y	66
DTR	Diurnal temperature range	°C	M	66
WarmDays	Warm summer days (maximum temperature > 20 °C) *	number of days	S/Y	66
ConWarmDays	Heat wave (consecutive number of days with maximum temperature > 20 °C)	number of days	Y	66
TropicNights	Tropical nights (days with minimum temperature > 17 °C)*	number of days	Y	66
CoolingDegDay	Cooling degree days (days with maximum temperature > 20 °C)	degree days	M/Y	66
DegDay20	Degree days with mean temperature above 20 °C	degree days	Y	66
DegDay17	Degree days for heating (mean temperature < 17 °C)	degree days	M/Y	66
ZeroCrossingDays	Zerocrossings (days with maximum temperature > 0 °C and minimum temperature < 0 °C)	number of days	S	66
VegSeasonDayEnd-5	End of vegetation period (last day of a consequtive period of 4 days with mean temperature < 5 °C	day number	Y	66
VegSeasonDayStart-5	Start of vegetation period (last day of a consequtive period of 4 days with mean temperature > 5 °C)	day number	Y	66
VegSeasonLentgh-5	Length of vegetation period (mean temperature > 5 °C)	number of days	Y	66
VegSeasonLentgh-2	Length of vegetation period (mean temperature > 2 °C)	number of days	Y	66
FrostDays	Frost days (minimum temperature < 0 °C)	number of days	S	66
SpringFrostDayEnd	Last day of spring frost (minimum temperature < 0 °C)	day number	Y	66
FirstDayWithoutFrost	First day without frost	day number	Y	66
ColdDays	Cold days (maximum temperature < –7 °C)	number of days	Y	66
PR	Precipitation	mm/day	M/S/Y	66
PRRN	Rainfall	mm/day	S/Y	14
PRSN	Snowfall	mm/day	S/Y	14
SuperCooledPR	Supercooled rain (Kämäräinen et al., 2018)	number of days	Y	13
PR7Dmax	Highest precipitation during 7 consequtive days	mm	Y	66
Prmax	Maximum precipitation intensity	mm/h	Y	66
PRSNmax	Maximum snowfall intensity	mm/h	Y	14
PRgt10Days	Strong precipitation > 10 mm/day	number of days	S/Y	66
PRgt25Days	Extreme precipitation > 25 mm/day	number of days	S/Y	66
DryDays	Dry days (with precipitation < 1 mm)	number of days	M	66
LnstDryDays	Longest dry period (with precipitation < 1 mm/day)	number of days	S	66
ET	Evapotranspiration	mm/day	M/S/Y	31
EffPR	Effective precipitation = precipitation-evapotranspiration	mm/day	S/Y	31
NetRO	Net runoff	mm/day	M(April-September)	24
SncDays	Number of days with snow cover	number of days	Y	42
SfcWind	Mean wind speed at the 10 m-level	m/s	S/Y	66
WindGustMax	Maximum gust wind speed at the 10 m-level (Gust wind is defined as the maximum wind speed from all integrated time steps per day)	m/s	Y	41
WindyDays	Number of days with gusts > 21 m/s at the 10 m-level (Gust wind is defined as the maximum wind speed from all integrated time steps per day)	number of days	Y	41
CalmDays	Number of days with wind speed < 2 m/s at the 10 m-level	number of days	Y	63
ConCalmDays	Number of consequtive days with wind speed < 2 m/s at the 10 m-level	number of days	Y	63
Wind975	Mean wind speed at the pressure level 975 hPa	m/s	S/Y	14
Wind975toSfc	Ratio between wind speed at 975 hPa and the 10 m-level	–	S/Y	13
Wind925	Mean wind speed at the pressure level 925 hPa	m/s	S/Y	14
Wind925toSfc	Ratio between wind speed at 925 hPa and the 10 m-level	–	S/Y	14
CalmDays975	Number of days with wind speed < 2 m/s at 975 hPa	number of days	Y	10
ConCalmDays975	Number of consequtive days with wind speed < 2 m/s at 975 hPa	number of days	Y	10
CalmDays925	Number of days with wind speed < 2 m/s at 925 hPa	number of days	Y	11
ConCalmDays925	Number of consequtive days with wind speed < 2 m/s at 925 hPa	number of days	Y	11
RhoS	Air density (2 m)	kg/m3	M	20
Rho925	Air density (925 hPa)	kg/m3	M	14
SD	Sunshine duration	number of hours	Y	14
RSDS	Downwelling shortwave radiation	W/m2	S	48
RLDS	Downwelling longwave radiation	W/m2	S	14
HumiWarmDays	Relative humidity > 90 % and mean temperature > 10C	number of days	S	24

(*continued on next page*)

Table 2 (*continued*)

Abbreviation	Climate indicator	Unit	Time period (M/S/Y)	N
ColdRainDays	Precipitation when the temperature lies between 0.58 och 2 °C	number of days	Y	66
ColdRainGT10Days	Precipitation (>10 mm/day) when the temperature lies between 0.58 och 2 °C	number of days	Y	66
ColdRainGT20Days	Precipitation (>20 mm/day) when the temperature lies between 0.58 och 2 °C	number of days	Y	66
WarmSnowDays	Precipitation when the temperature lies between −2 och 0.58 °C	number of days	Y	66
WarmSnowGT10Days	Precipitation (>10 mm/day) when the temperature lies between −2 och 0.58 °C	number of days	Y	66
WarmSnowGT20Days	Precipitation (>20 mm/day) when the temperature lies between −2 och 0.58 °C	number of days	Y	66
ColdPRRNdays	Rainfall when the temperature is below 2 °C	number of days	Y	14
ColdPRRNgt10Days	Rainfall (>10 mm/day) when the temperature is below 2 °C	number of days	Y	14
ColdPRRNgt20Days	Rainfall (>20 mm/day) when the temperature is below 2 °C	number of days	Y	14
WarmPRSNdays	Snowfall when the temperature is above −2 °C	number of days	Y	14
WarmPRSNgt10Days	Snowfall (>10 mm/ day) when the temperature is above −2 °C	number of days	Y	14
WarmPRSNgt20Days	Snowfall (>20 mm/ day) when the temperature is above −2 °C	number of days	Y	14
SST	Sea surface temperature (from the GCM)	°C	S/Y	23
SIC	Sea ice extent (from the GCM)	%	S/Y	17

stakeholders (Fig. 1). The method was inspired by a risk and vulnerability assessment method developed by Molarius et al. (2008).

In the first workshop the project climate scientists gave a brief explanation of numerical climate modelling and the limitations and advantages of climate scenario data. This was to give the stakeholders reasonable expectations of what could be achieved. Furthermore, challenges and risks for each sector were discussed, to improve the climate scientists' understanding of specific needs for climate information.

In the second workshop potential consequences identified by the experts were paired with climate indicators. For example: icing on wind turbine rotor blades is impacted by temperature, humidity and precipitation, especially at conditions close to 0 °C. This exercise resulted in lists of climate indicators to be further studied (Table 2) and also identified gaps where information could not be derived directly from the RCMs. An important element of the project was that the consequences should be identified by the sector representatives themselves, to make them involved in the process.

In preparation for the third workshop, based on RCM-derived indicators, the climate scientists presented an estimate of the likelihood of projected future change in a specific climate indicator at a national and regional level. For each indicator two climate scientists made individual assessments of the projected changes in ensemble mean and ensemble spread at different global warming levels. Combinations of change in mean and spread resulted in subjective estimates assigned with: "very likely", "likely", "less likely" and "not likely". Finally, the individual assessments were compared and merged in a dialogue between the two scientists. If the individual qualitative assessments disagreed, a common joint assessment was made. For some indicators the assignment "uncertain" was introduced, when it was not deemed possible to set a likelihood for change in the particular indicator. In parallel, the energy experts prioritised weather events to be studied in more detail.

In the third workshop, consequences identified as relevant were analysed further based on expert assessments. For each consequence the following assessments were made: First the likelihood that climate change, within the coming 20 years, will make the particular consequence more frequent or severe was estimated. From "unlikely" to "very likely" on the y-axis. Then the significance of the consequence on the energy system was estimated. From "not important" to "very important" on the x-axis. The assessments were first undertaken individually by each group member. Afterwards, the joint result was discussed within each WG, to give the participants the opportunity to adjust their assessments before the final result was concluded based on the average of the individual assessments. Each group assessment assumed that all other factors were unchanged.

Following the dimensions "likelihood of increase" and "likelihood of importance" (if the change were to occur), each consequence was sorted into one of three categories in a scatterplot (Fig. 2). If both the likelihood of increase due to climate change is "likely" or "very likely" and significance of the impact is "important" or "very important" the consequence is placed in the "Act" category. If only one of these likelihoods are estimated to be "likely"/"important" or "very likely"/"very important" the consequence is placed in the "Prepare" category. Consequences with low likelihood to be affected by climate change **and** of having significant impacts on the energy sectors are placed in the "Monitor" category. In some cases, it was not possible to say whether or in what way a consequence would be affected by climate change., for example, when the model ensemble members disagree on the sign of change of a climate variable. In these cases, it was not possible to place the consequence in the scatter plot. Instead, it was placed on a separate x-axis only describing only the likelihood of significant impact. This was done both to indicate that it was considered an important consequence not to be forgotten, and also to acknowledge the uncertainty in the climate signal. Such consequences should be monitored until more robust climate projections are available. In addition to placing the consequences in the three categories, an estimate was made of whether each consequence would be an opportunity or lead to negative impacts, and whether the opportunity/negative impact primarily has an impact on short-term operations, long-term operations or both. Based on the scatterplots, recommendations were made and conclusions drawn for each sector.

3. Results

3.1. Climate indicators

This section describes the general features of RCM-projected climate change in Sweden, focussing on what may be of relevance for the energy sector. Since it is not possible to describe the changes in all indicators from Table 2, we here focus on the eight most important indicators for the energy sector. For a more comprehensive presentation of results for a wider range of indicators see Blomqvist et al. (2021), Gode et al. (2021), Hansson et al. (2021), Kjellström et al. (2021), Sandgren et al. (2021).

Already at a global warming level of 1.5 °C the climate shows notable differences compared to the present, and even more so at higher warming levels. The climate change is, however, different for different variables, seasons and locations. Furthermore, the future climate will, as

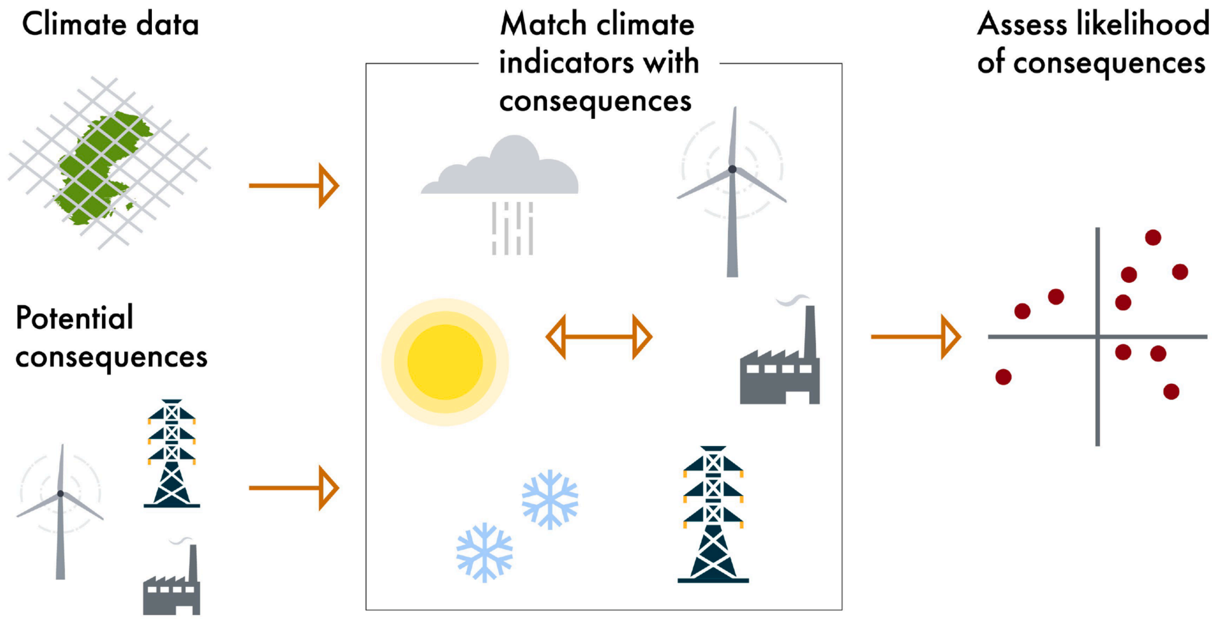

Fig. 1. The process of assessing consequences of climate change in the energy sector. Climate data are collected and explained by climate scientists. Potential consequences from climate change are identified by experts representing different parts of the energy sector. The consequences are then matched to climate indicators. Finally, the likelihood of climate change and its potential consequences is assessed.

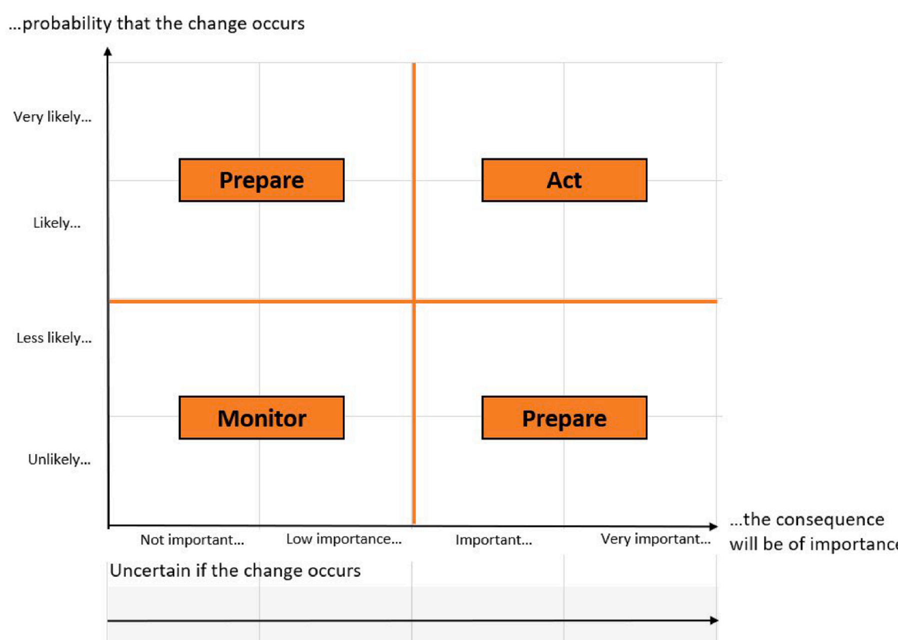

Fig. 2. Scatter plot for illustrating the results for the assessed consequences. The categories"Act", "Prepare" and "Monitor" aim to identify adaptation measures to be made to respond to climate change within the coming 20–50 years. Consequences placed in the "Act" category are likely to be made more frequent or severe by climate change and to have a significant impact. Some adaptation measures are required to meet climate change. Consequences placed in the "Prepare" category may be affected by climate change or may have an important impact. No immediate action is required, but preparations may be needed. Consequences placed in the "Monitor" category have a low likelihood of occurring but may be monitored in case the conditions change. In some cases, it was not possible to estimate the impact of climate change, for example when the climate model simulations disagree on the sign of change. Since these consequences are still important, and since it is possible to assess the impact, they are placed on a separate x-axis.

today's climate, show large variability between years and decades with alternating colder, warmer, drier and wetter conditions. All RCM projections agree that the most robust and obvious change is the temperature increase, especially in winter in the north. Higher temperatures will result in, for example: more warm and hot days, fewer frost days and cold days, and a longer vegetation period (Fig. 3 (see Supplementary Fig. S1 for a corresponding figure of GWL1.5)). The change in the number of days with zero crossings (days when the temperature rises from below 0 degrees Celsius to above, or falls from above zero degrees to below) is complex. Over the full year the average number of days is projected to decrease, since a warmer climate means fewer days with temperatures below zero degrees. In winter in northern Sweden, however, more days

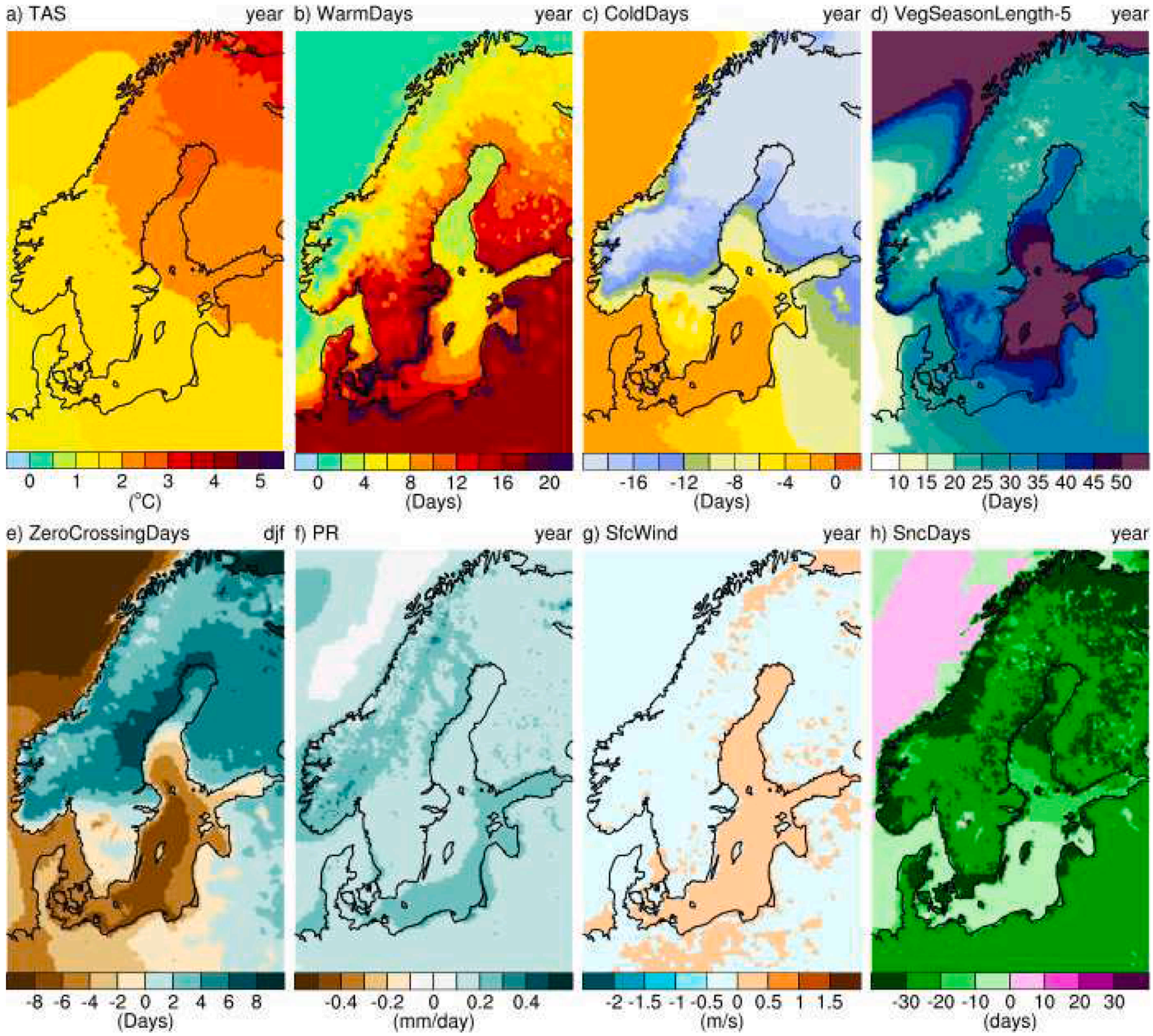

Fig. 3. Ensemble mean differences between GWL2 and the reference period 1971–2000 for a) average temperature, b) Number of warm days, c) Number of cold days, d) Length of the vegetation period, e) number of days with zero crossings, f) average precipitation, g) 10-metre wind speed, h) number of snow days. See Table 2 for definitions of indicators. All indicators are given as annual change except zero crossings which is given as change in winter.

are projected to be close to zero degrees in a warmer future, resulting in more zero crossings. In southern Sweden, on the other hand, the number of days with zero crossings will decrease also in winter.

The RCM projections generally point towards more precipitation through the year and more intense precipitation events. Despite this, problems with drought may increase, especially in the south, due to increases in evaporation associated with higher temperatures. A larger share of the precipitation is expected to fall as rain and less as snow. The average depth of snow cover and the length of the snow season are projected to decrease; however, the climate models show large differences in their capability to simulate snow which makes it difficult to draw detailed conclusions about snow cover changes. Despite decreasing depth of snow cover we note that intense snowfall events will still occur in the future, especially in the northern parts of Sweden. The average number of days with precipitation with temperature close to zero is projected to increase in large parts of northern Sweden and decrease in the south. Changes in the wind climate are projected to be small on average, both in mean and maximum wind speed as well as number of days with low and days with high wind speeds.

The high resolution used in the RCMs reveals detailed differences between inland areas and the coastal zone and between regions of high and low altitudes. It is, for example, clear that the number of warm days increases more along the Swedish south Baltic coast, that changes in wind speed are distinctly different over the Baltic Sea and over land and that the number of days with zero crossings increases in the elevated parts of southern Sweden, unlike in the surrounding areas (Fig. 3).

3.2. Identification of impacts and consequences

3.2.1. Bioenergy

Climate change can affect several factors that are important for the bioenergy sector (here focusing on forest-based bioenergy): potential for forest growth, storm felling, forest fires, game damage, snow damage, pest and fungal infestations (such as bark beetles and root rot), soil conditions and storage conditions for biofuels (Clarke et al., 2022; Bezner Kerr et al., 2022). These aspects lead to different consequences (including both gradual changes and sudden events) through factors such as increased/reduced growth, deteriorating timber quality, increased or uneven supply of biofuel, changed conditions for extraction of wood, increased storage needs and changing fire risk (e.g. Raffa et al., 2015; Brecka et al., 2018; Bezner Kerr et al., 2022).

For bioenergy, climate change means both a possibility of increased supply of biomass for biofuels but also an increased risk of aspects limiting the potential (Fig. 4). A longer growing season may enable increased extraction of wood and thereby more biofuels (Poudel et al., 2011). Concurrently, climate change may increase the risk of damage to the forest, such as infestation by bark beetles, forest fires and storm felling (Venäläinen et al., 2020), which can lead either to increased or reduced potential for bioenergy.

In the workshop it was concluded that bioenergy is sensitive to continued global warming, because the most important indicators (including temperature, length of vegetation period and precipitation) will clearly change in the future. For wind related factors there is no expected significant change. Yet, storm damage may increase due to changing soil conditions and changing exposure to bark beetles. The expected impacts are judged to vary significantly over the various consequences (Fig. 4). Some consequences are expected to lead to a relatively large impact (mainly increased forest growth), others may lead to a fairly large potential impact, however to varying degrees in different years (bark beetle outbreaks, forest fires, changed soil conditions and game damage) while other consequences (e.g. storm felling, snow damage and fungal infestations) are considered to be less important for bioenergy. In terms of forest growth, adaptation of forest management to climate change, for example through the choice of tree species, is a key measure for bioenergy. Nevertheless, while the potential increase in forest growth enables an increased biomass extraction, the final supply of biofuels also depends on how the demand for other purposes develops. Thus, the total overall impact of climate change for bioenergy in general (whether it is positive or negative) is not possible to determine because the assessment does not cover the scale of the opportunities or negative impacts in detail.

3.2.2. *District heating and cooling*

The climatic factors identified as most important for district heating and cooling are temperature, precipitation and humidity. Based on the RCM projections it is considered very likely that temperature will increase throughout Sweden and during all seasons. It is also likely that precipitation will increase throughout the country, with a possible exception in summertime in southern Sweden. However, since the natural annual variability of precipitation in the short term is larger than the climate signal, the significance of the change is uncertain.

Heating and cooling demand is expected to change in all areas of the country. This will have significant consequences even if global warming is limited to under two degrees. (Note that only the likelihood of change in demand is estimated in the scatterplot; whether the impact is positive or negative is then based on whether the demand is increasing or decreasing (Fig. 5)). A number of analyses were assessed for different GWLs, including change in annual and peak demand for different parts of the country, different types of buildings and different seasons. District heating and cooling actors need to consider such changing market conditions and adapt their business models according to the expected changes in heating and cooling demand. Reduced heating demand affects the potential for the production of locally controllable combined heat and power. This controllable power production is increasingly needed in Sweden because of the expected increase in electricity demand and the slow expansion of the electricity grid. Increased precipitation and moisture amplify the likelihood of sudden events such as floods, landslides and fires in fuel storages. As the likelihood increases, new adaptation measures may be required. This is particularly important because trends in precipitation and humidity may be hidden by natural variations.

In the workshop it was judged that all climate indicators identified as having an impact will increase, with a relatively high likelihood (Fig. 5). Temperature changes will likely have consequences, for example via changed demands for heating and cooling. The sector has already experienced a change and has started to adjust, but further adjustments are needed. Negative consequences associated with changes in precipitation are judged to be less likely.

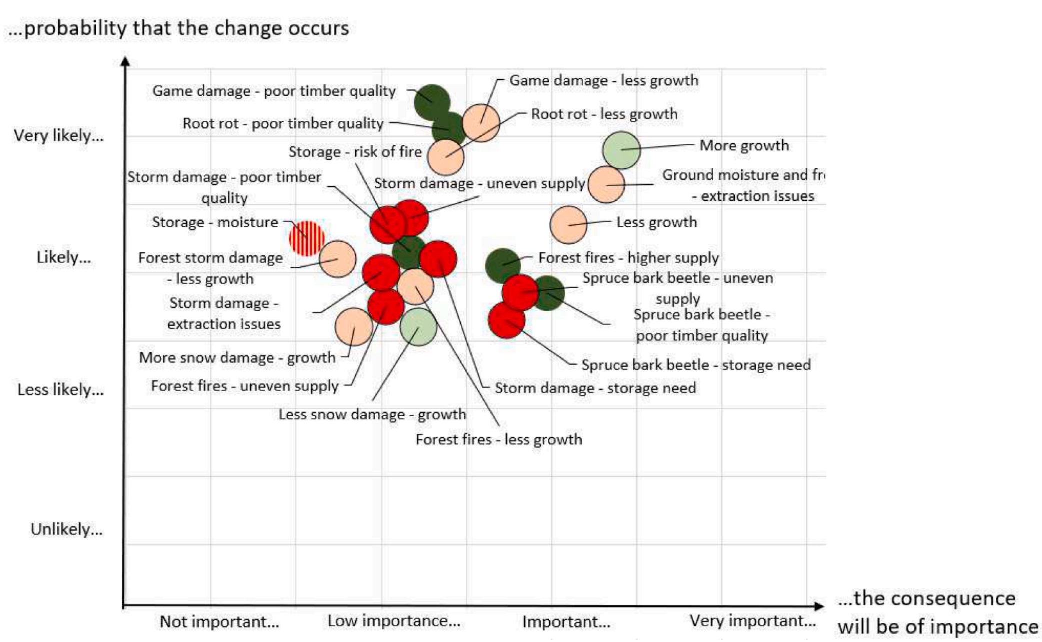

Fig. 4. Scatter plot for bioenergy. Green colours: the consequence represents an opportunity for the sector. Red/orange colours: the consequence will lead to negative impacts. Light colours: the consequence impacts long-term operations and conditions. Dark colours: the consequence has short-term impact on operations. Vertical stripes: the consequence affects operations both in the long-term and short-term. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Scatter plot for the district heating and cooling sector. Green colours: the consequence represents an opportunity for the sector. Red/orange colours: the consequence will lead to negative impacts. Light colours: the consequence impacts long-term operations and conditions. Dark colours: the consequence has short-term impact on operations. Vertical stripes: the consequence affects operations both in the long-term and short-term. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2.3. *Hydropower*

The direct impact of climate change on hydropower is essentially a question of how changes in precipitation and temperature relate to a change in conditions for electricity generation and the ability to regulate at various time scales. Since hydropower is the primary resource to adapt to variations in electricity demand on hourly to seasonal scale in the Swedish electricity system, there also exists an indirect impact through changes in electricity consumption patterns and changes in production pattern of wind and solar power (Bruce et al., 2016; Löfblad et al., 2021). Precipitation and temperature are thus the two most important weather and climate related factors. Both the annual average precipitation and the distribution of precipitation over the year is of relevance, where a more even distribution of water resources over time facilitates the turnover of water resources to electricity production with existing installations. Temperature has a key impact on how precipitation translates to inflow in rivers, lakes and dams through its impact on evaporation and on the form of precipitation (rain or snow). The Swedish hydropower capacity is primarily located in the north where precipitation falls as snow during a large part of the year. The share of precipitation falling as snow and the timing of the spring flood strongly impact hydropower operation and the ability to translate increased precipitation to increased electricity production. Temperature also has an impact on ice on the reservoirs. As ice settles on the dams, the production level in the hydropower stations is limited. Longer ice periods could reduce the ability of hydropower to manage variations in the electricity system. The analyses carried out here include potential impacts of increased annual precipitation, changes in the precipitation and river flow seasonality, intense precipitation, drought, increased water temperatures and ice formation.

Increased precipitation and inflow may lead to increased hydropower production. To what extent this can be realised depends on factors as evaporation and the availability of storage capacity. Previous studies have concluded that climate change could imply an increased potential for hydropower production in Sweden (Gode et al., 2007; Koestler et al., 2019). This study has not been able to confirm the robustness of that conclusion, mainly due to a lack of hydrological inflow data based on the EURO-CORDEX data (Schaffer et al., 2023). But also because the external conditions for hydropower in Sweden's energy system are in transition, implying that the role of hydropower in Sweden will probably be significantly different in the coming decades compared to today (Gode et al., 2022; Scharff et al., 2022). The WG concludes that it is highly likely that the current development and transition of the energy system, not the least along with forthcoming changes in the environmental regulation that will affect hydropower's abilities, will have a greater impact on hydropower than the change in climate that we currently foresee. Key factors are the swift growth in wind power in the highly interconnected north European energy system, implying increased variability in the electricity production, and expectations of a significant increase in electricity demand. All of these factors will lead to new production conditions for hydropower.

However, this does not mean that climate change is of no significance for hydropower. Climate change needs to be taken into consideration when the electricity system of tomorrow is designed and developed. The hydropower operators are highly experienced in handling variations in both weather and fluctuations in supply and demand in the energy systems but, nevertheless, climate change will present an additional component that needs to be taken into consideration in the long-term planning of hydropower.

*During the discussions with the WG representing hydropower it was found to be more difficult to draw general conclusions on the impacts and probabilities of climate change on hydropower compared to the other parts of the energy sector. This was partly explained by the very specific and local conditions applying to single hydropower plants and their owners, with large variations in type of plants, storage capacities of the reservoirs and locations. Geographic differences are seen on the large scale (*e.g. *north or south of Sweden, high-altitude or low-altitude), but also within the different river systems (comprising multiple interdependent hydropower plants, owners and reservoirs). This made it difficult to come to any clear consensus on how the hydropower sector needs to handle the impacts of climate change. Nevertheless the current project established a collaboration between relevant parties and pointed out a direction for further work.*

3.2.4. *Nuclear power*

Past weather events have occasionally had negative effects on the operations and availability of nuclear power in Sweden and Finland, although to a very small extent. An increased number of weather-related operational disturbances due to climate change is not considered to jeopardise safety in general, and is seen only as a matter of operating economy and security of electricity supply. Incidents of relevance include lightning that may impact external and internal electricity grids, and a warmer sea that in extreme cases may lead to power reduction (or even temporary shutdown), as well as more incidents with marine organisms clogging cooling water intakes. A warmer sea has a negative effect on thermal efficiency and thus on electricity production, although probably of relatively little importance for the yearly production. Since all nuclear power plants in Sweden and Finland are located on the coast, sea-level rise is also a factor to consider. However, sea level rise is not expected to require any extra preventive measures at the nuclear power plants until the end of this century (Hieronymus and Kalén, 2020). After that, in a climate scenario with extensive global temperature increase and considering extreme weather events with a return time in the order of 10,000 years, sea-level rise may become a problem for reactors located in southern parts of Sweden. For the more northern nuclear power plants, the land uplift will compensate for the sea level rise for a long time to come.

Dealing with possible consequences of a changing climate is for the nuclear power plant owners in many ways an economic issue, and for the surrounding electricity system a matter of security of supply. One example is reduced cooling due to increased sea temperature, which can be remedied by investing in increased heat exchanger capacity or relocating cooling water intakes to deeper and colder water. These are examples of measures associated with relatively high costs. Another example is lightning strikes. A number of protection measures have been implemented over the years and it is estimated that additional measures are available if it turns out that climate change leads to, for example, more powerful lightning strikes. In this case, the range of available measures is judged to be relatively inexpensive. Measures aimed at the external grid are, on the other hand, beyond the control of the power plant owner.

In the nuclear power industry safety assessments (including extreme weather events) are, for obvious reasons, a natural component of the operations. The relatively simple approach presented here cannot replace the well-established methods for assessing hazards already used within the sector. Therefore no scatterplot was made. Instead, the discussion within the WG could help updating and revitalising these methods.

3.2.5. *Wind power*

The most important climate related factors for wind power are changes in wind power production potential, wind speed pattern over the year and ice formation (Fig. 6). Overall, consequences seem to be relatively small, because the RCM projections do not indicate that there will be any major changes in wind conditions, although the results are uncertain with large differences between individual RCMs. Potential increase in ice formation in northern Sweden during winter due to more humid conditions and temperatures more frequently close to 0 °C is a more certain climate signal with a high negative consequence, which means that the wind power industry needs to act to reduce these risks.

There are several other potential consequences of climate change that the wind power industry needs to prepare for, for example episodes with calm wind or strong winds. Several consequences of climate change are also expected to have a positive effect on wind power. Examples of this are reduced icing in southern Sweden and reduced sea ice in the Baltic Sea that can facilitate the expansion and maintenance of offshore wind power.

Variations in wind power production are reduced if wind power is spread geographically, which means that negative impacts linked to

Fig. 6. Scatter plot for the wind power sector. Green colours: the consequence represents an opportunity for the sector. Red/orange colours: the consequence will lead to negative impacts. Light colours: the consequence impacts long-term operations and conditions. Dark colours: the consequence has short-term impact on operations. Vertical stripes: the consequence affects operations both in the long-term and short-term. Consequences for which the impact of climate change is uncertain are placed on a separate x-axis. Showing that the consequences are important and should be monitored further. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

calm conditions are reduced (Grams et al., 2017). This, however, requires sufficient transmission capacity. There are nevertheless periods with very low wind throughout northern Europe. These situations, although rare, are the biggest challenge for the electricity system. A continued strong expansion of wind power means that in the long run it will constitute a very large share of Sweden's electricity supply, which means that potential consequences of climate change on wind power can have major impact on the electricity system.

In the workshop on wind power, all indicators related to wind were judged to be uncertain, but the consequences of these changes, if they were to occur, were judged to be large. Since it was not possible to set a likelihood on the impact of climate change, these consequences were placed on a separate x-axis, showing that the consequences are important and should be monitored further. Positive consequences are increased mean wind speed; negative ones are decreased wind speed and more windstorms. The factor most likely to change due to global warming is the frequency and impacts of icing on the rotor blades. This will change in a warmer climate, but the effect varies between regions of the country and times of the year. In southern Sweden a warmer climate would generally lead to fewer problems with icing, while in the north it could lead to more problems especially during winter. This means that incidence of icing moves north and over the year becomes less of a problem for the sector as a whole, even though local variations are large.

3.2.6. Power grid

Climate related consequences for the power grid constitute both high-impact rare events and those that affect day-to-day operations. The most important factors are ice and snow conditions, temperature, lightning, and strong winds. Most climate change consequences are negative, but there are geographical differences. For example, some snow and icing problems are expected to increase during winter in northern Sweden, while they are generally expected to decrease in other seasons and year-round in southern Sweden (Fig. 7). In the south, instead, increased risk of forest fires is expected to be the most serious change, while risk of forest fires is considered to remain unchanged in the north. We note that these factors already affect the power grids to varying degrees today, and that the power grid companies are already taking a range of measures (Swedish Energy Markets Inspectorate, 2022). Above all, they have made major investments in burying a large proportion of the local grids' overhead lines.

Although we have tried to describe different consequences separately in the analysis, we note that they are largely connected. For example, the consequences of ice and snow build-up on power lines and trees can be exacerbated by high wind speeds. Likewise, the consequences of forest fires can be significantly worse if there are strong winds at the same time. One aspect of the consequences of climate change is that certain weather phenomena are significantly worse in other parts of the world. Examples include lightning and heat waves which are much more common in, for example, parts of Australia and the USA. This means that it is obviously possible to handle such phenomena, but major measures may be required.

4. Discussion

4.1. Quality and representativeness of climate models

In general, the regional climate models used here are too cold and too wet, compared to observations. Given these systematic errors, and the lack of bias-adjustment to minimise them, we are careful not to do detailed or local descriptions of climate impacts. Models that are too wet and cold may overestimate the problems of e.g. icing or floods. Furthermore, indicators based on thresholds may be sensitive to even small deviations from the actual climate. Based on these data it is difficult to quantify the impact of climate change. The RCMs do,

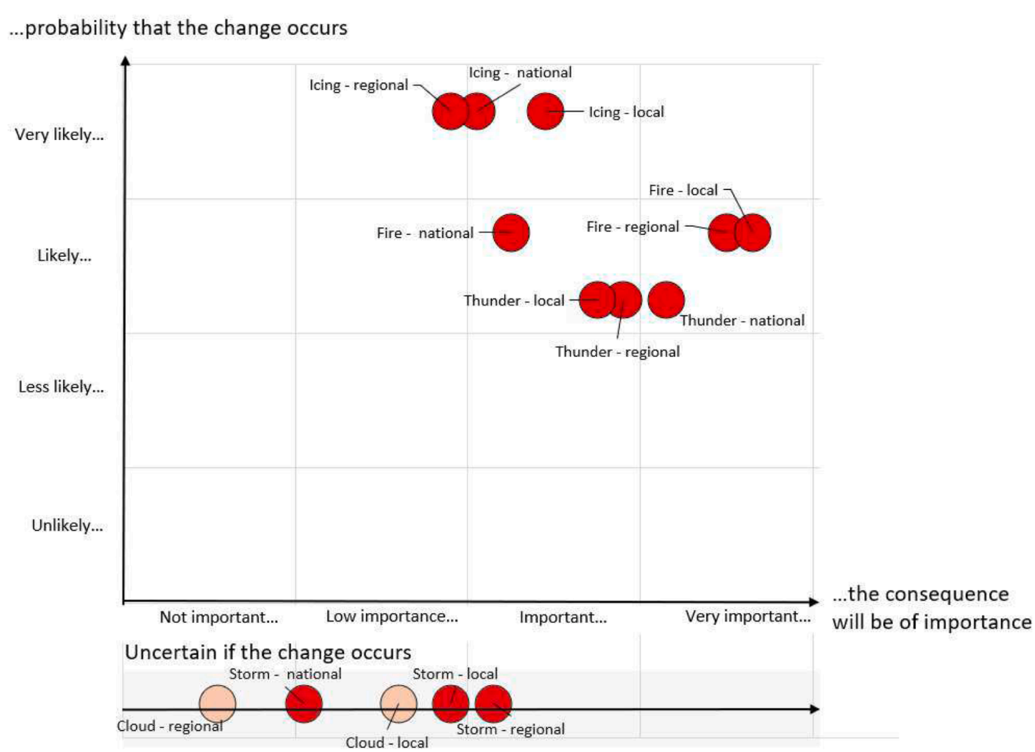

Fig. 7. Scatter plot for the power grid. Green colours: the consequence represents an opportunity for the sector. Red/orange colours: the consequence will lead to negative impacts. Light colours: the consequence impacts long-term operations and conditions. Dark colours: the consequence has short-term impact on operations. Vertical stripes: the consequence affects operations both in the long-term and short-term. Consequences for which the impact of climate change is uncertain are placed on a separate x-axis. Showing that the consequences are important and should be monitored further. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

however, agree more on the trends than on the absolute values. Thus, it is possible to make qualitative statements about the extent to which impacts or consequences are projected to be more likely, which is sufficient to indicate where adaptation measures are needed. It should be noted that the relatively coarse resolution in the EURO-CORDEX ensemble limits the possibility to make detailed descriptions of local climate conditions. Analyses of changing conditions for wind power would especially benefit from higher model resolution. We also note that the chosen method is subject to individual judgements. For instance, local details in RCM performance or climate change signals may be perceived as more or less important by the individual researcher performing the assessment. Another researcher might come up with different conclusions or stress other factors, regions or impacts. We aimed to minimise the degree of subjectivity by having two climate researchers do their own individual assessments that were then compared. Similarly, to minimise the effect of differences in the understanding and interpretation of the consequences, the individual interpretations of the impacts were discussed in the WGs. However, another set of participants may have produced a different outcome.

4.2. Assessment of climate change, consequences and constraints from policy

An assessment of the combined effect of climate change on the energy system requires knowledge about both the energy system and the climate of the future, and thus requires cross-sectoral and/or interdisciplinary cooperation. The development of the energy system is governed both by factors that are relatively well known and factors that are associated with large uncertainties. The future energy system in Sweden and northern Europe will most likely be characterized by a much larger share of renewable energy, mainly wind power, than today. Knowledge about the impact of climate change on different parts of the energy system is thus of large importance in a systems perspective.

More detailed knowledge about the impacts of climate change on the energy sector as well as the effect of different measures and the need for relevant policy development is needed. Some of the climate change impacts may also increase the probability of other consequences. For example, in the case of bioenergy storm felling and forest fires leads to an increased risk of bark beetle outbreaks. Such chains of events and consequences would also be of interest for further studies.

Weather and climate related factors already have a strong impact on the energy system today. For example, several of the most common causes of short duration power outages are directly or indirectly weather related. The annual hydropower production varies between dry and wet years, and the energy demand is affected by temperature, sunshine and more. Climate change brings a variety of consequences on the energy system – increased risks and changed conditions but also new opportunities, such as an increased potential for hydropower production due to increasing precipitation.

We suggest a few generic steps that could be used as a guide in a co-production process for the energy sector. The steps are not independent, and could be taken either one at a time or in parallel: raise awareness of local variations in climate change; work to better understand the consequences for each energy sub-sector and source, prioritise these and initiate measures linked to this; monitor climate change and its consequences, to be able to determine the needs for further research and development; identify responsible actors and stakeholders and establish effective collaborations; learn from others, e.g. from other countries, but also from other industries or sectors that have similar issues.

5. Conclusions

In Sweden, the projected climate change implies a gradually warmer climate. The warming is projected year-round but is expected to be strongest in winter. The number of warm days will continue to increase, and hot extremes will be more frequent. Cold extremes will be less frequent, and the number of cold days and days with snowfall will decrease. Precipitation is projected to increase in all seasons in all parts of the country. A larger proportion of the precipitation will fall as rain, and less as snow. The size of future changes depends primarily on the magnitude of future emissions of greenhouse gases but the time perspective is also important and we note that natural variability can amplify or weaken the projected trends for periods of decades or more.

Climate change will have an impact on the Swedish energy system, both through gradual changes and through sudden events. Gradual changes alter the conditions for the energy systems but also allow time to adapt. Our results show how conditions for power and heat production change, for example due to changing amounts of precipitation, length of snow season, wind speed etc. The demand for different types of energy will also change as a result of climate change; as an example, the demand for heating and cooling will be different in a warmer climate. Sudden events will affect power and heat production directly. Forest fires, windstorms and floods may disrupt production and transmission or damage production plants. The discussions between climate scientists, energy experts and stakeholders from the energy sectors in the workshops also identified a number of indicators that are currently not possible to derive from the RCMs (e.g. temperature in the sea, sea ice extent, average sea level), or not simulated at all by most climate models (lightning, hail storms, near-ground level ozone concentrations); these, therefore, could be a starting point for future studies.

The impact of climate change varies from sub-sector to sub-sector. Hydropower and wind power, for which the production is naturally linked to weather and climate, are significantly impacted by climate change, although the interdependence of these power production types (with hydropower's very important role in balancing variations in energy production) may have larger consequences from a systems perspective compared to climate change. For other sub-sectors, such as nuclear power, other factors such as policy and technology developments are more important. The effect of climate change on a certain type of power production also depends on its role in the future energy system. As increased electrification is expected in Sweden the demand for renewable energy is expected to increase further and then mainly as wind power. A system relying on wind power is more sensitive to day-to-day weather variations than a system relying on hydropower or nuclear power. With increased contribution of wind power the impact of climate change on this sector may increase, but needs to be studied further. Immediate action for climate change adaptation is in most cases not required. Instead, climate change adaptation should be a part of new/re-investments and other measures to adapt to gradually changing climate and weather conditions. There is a need for continued work and research on measures to reduce negative effects and contribute to positive consequences of climate change for the different energy sectors.

To assess the impact of climate change on the energy system is to assess the combination of two complex systems, the energy system and the climate system. It is therefore efficient and valuable to initiate studies and forums where climate experts can meet with experts from the different energy sectors to discuss and decide on vital and relevant climate adaptation measures. The series of workshops held in this study, where different aspects of climate change and consequences were discussed, proved very successful and has increased our understanding of climate impacts on the energy system.

CRediT authorship contribution statement

G. Strandberg: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **P. Blomqvist:** Conceptualization, Investigation, Methodology, Writing – review & editing. **N. Fransson:** Conceptualization, Investigation, Methodology, Writing – review & editing. **L. Göransson:** Conceptualization, Investigation, Methodology, Writing – review & editing. **J. Hansson:** Conceptualization, Investigation, Methodology, Writing – review & editing. **S. Hellsten:** Conceptualization, Investigation, Methodology,

Writing – review & editing. **E. Kjellström:** Conceptualization, Investigation, Methodology, Writing – review & editing. **C. Lin:** Formal analysis, Investigation. **E. Löfblad:** Conceptualization, Investigation, Methodology, Writing – review & editing. **S. Montin:** Conceptualization, Funding acquisition, Writing – review & editing. **E. Nyholm:** Conceptualization, Funding acquisition, Writing – review & editing. **A. Sandgren:** Conceptualization, Investigation, Methodology, Project administration, Writing – review & editing. **T. Unger:** Conceptualization, Investigation, Methodology, Writing – review & editing. **V. Walter:** Investigation, Writing – review & editing. **J. Westerberg:** Conceptualization, Investigation, Methodology, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

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