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Projected patterns of climate change impact on photovoltaic energy potential: A case study of Iraq

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ABSTRACT

Ambitious plans for the decarbonization of the global energy system necessitate the scaling up of renewable energy exploitation. This could render the energy supply system more susceptible to the effects of climate change as most renewables are climate-dependent by nature. Therefore, understanding the consequences of climate change on renewable energy systems at a regional level plays an important role in the financial management, process optimization, and energy yield assessment of these systems. In this work, the key objective is to examine the projected impacts of surface insolation and temperature fluctuations on the future photovoltaic (PV) energy potentials in Iraq. Projections are quantified across two climate scenarios, RCP4.5 and RCP8.5, which represent the intermediate and worst-case scenarios in which insolation will rise by 4.5 and 8.5 W/m^2 by the beginning of the next century. The results show that the average temperature across the country is anticipated to rise by 1.5 °C and 2.4 °C under RCP4.5 and RCP8.5, respectively. The results also show that the change in solar PV potential relative to current climatic conditions, would be −0.3 to 8.1% under RCP4.5 while it is −5.1 to 6.3% under RCP8.5 by the beginning of the next century. The highest potentials are predicted in the western parts, and the greatest drops are in the southeastern parts. Temporal stability of PV potentials also appears to be little affected by future climatic scenarios, with some southern parts even indicating a little positive rise. So, even though climate change is expected to cause small drops in PV output in some areas, it is unlikely to pose a danger under RCP4.5 to PV productivity in Iraq.

1. Introduction

The ambitious plans for the transition towards renewable energies as part of climate-change mitigation targets may expose the global energy supply system to more instability and unpredictability as a result of climatic variations [1]. This is due to the fact that the majority of renewable energy sources are weather-and climate-dependent, which in turn may exacerbate intermittency, complicating the planning and marketing of several renewable technologies. Consequently, many low-carbon energy supply strategies may become challenging to adopt in the future. Therefore, the availability of reliable information on the impact of climate change on the productivity of renewable energy systems is so crucial for optimal operation, yield maximization, and supply management of these systems [2]. Solar energy ranks first on the list of the world's sustainable energy sources owing to its availability and more fairly geographical distribution than any other sources, such as wind, hydropower, biomass, etc [3,4]. On a global basis, photovoltaics are considered the fastest growing renewable energy conversion technology in terms of installed capacity, owing to their continuous cost reduction and technical maturity [5].

According to the International Renewable Energy Agency's marketing forecasts, the share of renewable energy in the global energy system is predicted to grow by 50% between 2020 and 2025, with solar PV accounting for about 60% of this growth between 2020 and 2025 [6]. However, the sensitivity of PV power outputs to climate change is a limitation that has to be managed. For example, PV conversion efficiency is influenced by atmospheric temperature (T), and thus, colder temperatures usually boost it while hotter ones decline it. Meanwhile, air movement often cools the PV module, so the surface wind speed has an effect on the patterns of PV yields too. Climate models are the only option to undertake climate forecasts and to investigate the viability of alternative energy systems in the long term. Regional climate models, which enable fine prediction at the expense of a narrower domain than global ones, are the most appropriate means for regional analysis

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objectives.

Many studies have sought to uncover the implications of climate change on solar PV yields and concluded that climate change must be included in planning for future PV projects. Previous studies generally adopted two climatic models, which are RCP4.5 and RCP8.5. The first model represents the intermediate scenario in which insolation is expected to increase to 4.5 W/m^2 by 2100, while the second model signifies the worst-case scenario in which insolation will increase to 8.5 W/m^2 by 2100 [7–10]. Crook et al. [11] determined that PV production in Europe and China will likely rise by a few percent over the twenty-first century, while remaining stable in Algeria and Australia and declining by a few percent in the western United States and Saudi Arabia. Gaetani et al. [12] projected a decline in the PV production in eastern Europe and northern Africa by 7% with a 10% rise in western Europe and the eastern Mediterranean by 2030. Jerez et al. [10] indicated that the PV production during the twenty-first century in Europe will change by −14 to +2% relative to projections made under present climate conditions, with the highest declines occurring in Northern countries and lowest increases occurring in Southern countries. Ma et al. [13] indicated that there is a relation that is very close to linear between the rise in the air temperature of the air and the rise in the amount of solar radiation over the period 2030–2050 that require an increase in economic costs of 10–20% for roof-based PV systems to be installed in Austuralian cities. Panagea et al. [14] conducted an analysis of future climate changes on insolation and temperature in Greece and concluded that photovoltaic modules will benefit from the climate changes with a 4% higher energy output is expected by 2100. Wild et al. [15] anticipated that the future production of concentrated solar power (CSP) systems are four times larger as compared to the future production of PV systems worlwide. Yin et al. [16] used satellite data and the results of climate models to study the effects of intermittent solar input on future PV reliability. They found that PV productivity is more sensitive to changes in mean solar radiation in hot, dry places than in other places.

Using the most aggressive climate change scenario of warming level (4.0 °C), Santos and Lucena [17] estimated that the techno-economical capacities for contribution of PVs in Brazil would fall by 0.84 and 0.008%, respectively by the end of century. Hou et al. [18] projected positive feedback of the climate change mitigation scenario (SSP1-2.6) on solar PV potential in Europe, with an increase of PV output by around 5% independent of season or region. Tahir et al. [19] anticipated that the PV energy yield will drop by 8.0–8.4% between the years 2020 and 2080, and compared to monofacial PV, bifacial PV has a greater power output and be less impacted by the air temperature and humidity. The analsis by Bichet et al. [20] revealed that the annual solar potential is likely to decline on average by 4% throughout the African continent by the beginning of the next century. Feron et al. [21] projected that summer days with reduced solar photovoltaic production will double by 2050 in the Arabian Peninsula, whereas in southern Europe, they are projected to drop by 50% during the same interval.

Iraq offers substantial feasibility for solar energy exploitation owing to the relatively long irradiation duration of around 3250 h per year with an annual average intensity of 5.4 kWh/m^2/day [22,23]. This enables solar-based power generation to serve as a practical alternative to satisfy the national growing energy demand and contribute to the reduction of greenhouse gas emissions in the climate change context. The semi-arid climate regrettably puts the country at serious risk from climate change consequences. According to the United Nations Environment Program, Iraq is ranked as the fifth most vulnerable country to the impacts of climate change in the world [24]. To date, however, there has been very little discussion regarding the future patterns of climate change and their effects on the PV production potentials over Iraq. This study seeks to assess the climatic change impacts on the local climatic patterns and their associated risks on the future PV potentials in Iraq. The results could provide an insight on the possible risks of PV module degradation and failure, guiding to develop proper material selection and more effective technical solutions. A set of 18 regions of the state-of-the-art geographic information system from CMIP5 is adopted under two climate change scenarios (RCP4.5 and RCP8.5). Annual variations in surface temperature, sky insolation, and their effects on the PV potentials are predicted for four future projection periods (2020–2040, 2041–2060, 2061–2080, and 2081–2100). The yearly response of solar irradiation, temperature, and PV energy yield are presented and discussed in details. The results are expected to serve as a guideline for planning future investments in solar PV projects based on updated climatic projections that made available to the scientific community on a local scale.

2. Study area

Iraq is a Middle Eastern country in Western Asia being located between latitude lines 29.5° and 37.22° north and longitude lines 38.45° and 48° east. Iraq is generally classified into four climate zones as shown in Fig. 1. Region I: climate typical to the Mediterranean region with mountains in the north and northeast parts, and accounts for around 21% of the total land area. Region II: climate of the steppe in the submerged zone located in the south and west parts, accounting for about 9.6% of the total land. Region III: climate being classified as subtropical in the central and southern regions (Mesopotamian Plain) accounts for almost 30.2% of the total area. The last region is Region IV: climate of the continental desert exists in the west regions, which accounts for approximately 39.2% of the total region [25].

Iraq generally has climates of the continental and subtropical semi-arid types, except for the mountainous parts in the north and northeastern regions, which have a Mediterranean climate. Winters are generally mild, with temperatures ranging from chilly to cold, whereas summers are hot and dry, with temperatures ranging from hot in the north to extremely hot (greater than 45 °C) in the south [26]. The semi-arid climate puts the country at serious risk from climate change consequences. These consequences are manifested in the form of recurring droughts, erratic precipitation patterns, increasing desertification, and sandstorms. Moreover, the water supplies of the Tigris and Euphrates rivers, both of whose catchment regions are adversely affected by the same driving climate elements.

3. Data source

The Community Climate System Model (CCSM) version 4 was adopted in this case study for the climatic projections. This climate model is a part of the Coupled Model Intercomparison Project 5 (CMIP5) [28]. It is conserved by the National Centre for Atmospheric Research (NCAR). Climatic projections based CCSM model are available for download in Arc GIS format as shapefiles for the years 2020–2100. The RCP4.5 and RCP8.5 projections for air temperature and surface insolation are also available for download from the same source as monthly mean data.

4. Mathematical modeling

For estimating how climate change could affect the PV power production in the next decades, the PV cell temperature has to be first parameterized as a function of the influencing climatic parameters that are estimated based on the RCP4.5 and 8.5 models. These climatic parameters are mainly solar insolation, surface temperature, and/or wind speed. They are usually provided by the PV module manufacturers as Standard Reference Environment (SRE) for nominal operating conditions. The SRE typically sets the total insolation at 1000 W/m^2, surface temperature at 25 °C, and wind speed at 1 m/s [29]. According to Coskun [30] and other studies [31–34], there are different approximations to obtain the PV cell temperature as a function of the climatic variables, but all these approximations assume that the PV potential is linearly dependent on the three climate variables mentioned above. This is because the sensitivity analysis, which serves as the basis for

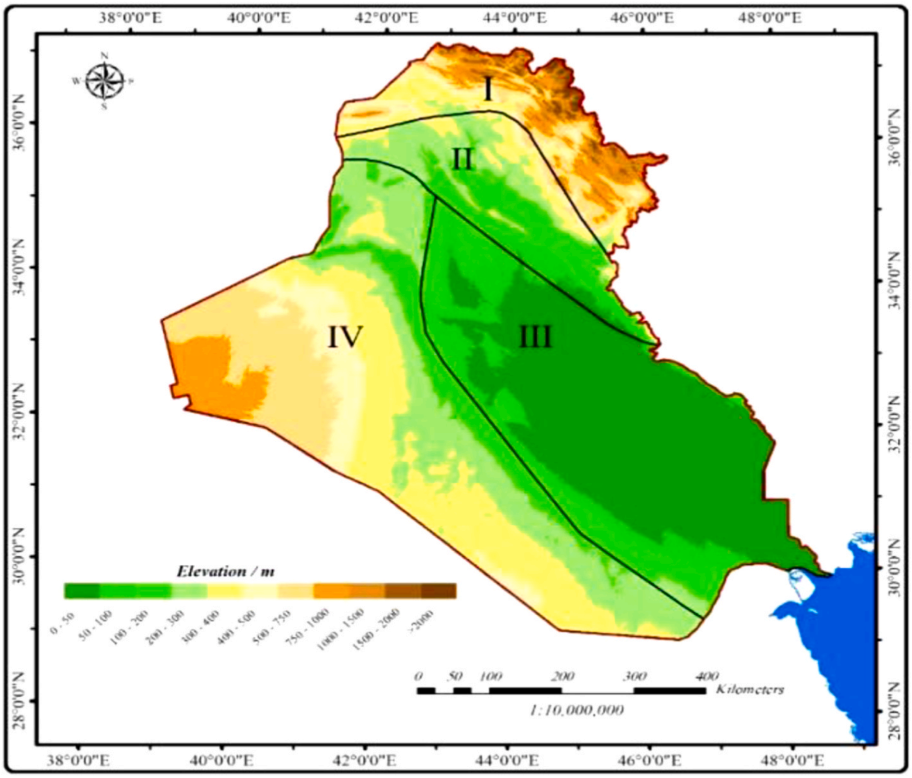

Fig. 1. Study area and climatic zones [27].

determining the parameters involved, is not an easy process, particularly when an insolation simulator is unavailable, which is the case in most situations [34].

The productivity of PV modules on a site is typically governed by two factors: the local PV energy potential (PV_{POT}) and the total installed capacity of the site. PV_{POT} is basically a dimensionless parameter that indicates how well the PV modules perform in comparison to their nominal power capacity under actual environmental conditions. According to the literature [35], it can be expressed as:

$$PV_{POT} = P_R \frac{I}{I_{STC}} \tag{1}$$

Where I_{STC} is the solar insolation implemented on PV modules under standard test conditions $(1000\ \mathrm{Wm}^{-2})$, I is the insolation striking the PV front surface, and P_R is the performance ratio, which accounts for the impact of PV temperature (T_{Cell}) on the overall PV conversion efficiency. It is theoretically equal to 1 when the ambient conditions meet the manufacturer's standard operating conditions (STCs), and less (or more) than unity when ambient conditions vary from the typical STCs. According to former literature [10], P_R is estimated as:

$$P_R = 1 - \gamma(T_{Cell} - T_{STC}) \tag{2}$$

where T_{STC} is the temperature of the PV cell while it is being tested under standard circumstances (25 °C), and γ is temperature coefficient which is assumed to be equal to 0.005° Celsius per second for monocrystalline silicon cells [8]. Consistent with equation (2), the cell temperatures greater than 25°C lead to poorer performance ratios (P_R). T_{Cell} is affected by the main metrological data of the site which are: the air temperature (T_a), the incident insolation (I), and the wind speed (u_{wind}). It can be formulated as [7,10,35–37]:

$$T_{cell}(C) = c_1 \cdot T_a(c) + c_2 \cdot I(c) + c_3 \cdot u_{wind}(c) + c_4 \tag{3}$$

Where c_1, c_2, c_3, c_4 are empirical coefficients mounting the heat exchange effects between the solar PV module and the surroundings. According to Ref. [38], these parameters are defined as $c_1 = 0.943$, $c_2 = 0.028^{O}\mathrm{CW}^{-1}\mathrm{m}^2$, $c_3 = -1.528^{O}\mathrm{Cm}^{-1}\mathrm{s}$, and $c_4 = 4.3^{o}\mathrm{C}$. Equation (3) can simplify the computation of the effects of climatic parameters on PV_{POT} by assuming linear effects of the cell temperature. Therefore, average daily estimations of T_a, I and u_{wind} enable the computation of the daily PV_{POT} values by applying equation (1) through (3). For estimating PV_{POT} for the period 2020–2100, estimations are made consistent with the two scenarios of interest: RCP4.5 and RCP8.5.

5. Results and discussion

The variability of climate-change impacts on PV power potential is strongly dependent on the region and can be investigated by analyzing the local variations of climatic variables across the region studied. Atmospheric temperature, surface insolation, and wind speed are among the most influential variables that govern the productivity of PV systems. Higher wind speeds generally increase PV efficiency. However, their variability must be substantially greater than that of atmospheric temperature and horizontal insolation to produce a significant effect on PV power potential. Therefore, the focus is given to evaluating the effect of atmospheric temperature and insolation on the future PV power potentials in Iraq. Two mitigating emission scenarios are adopted (RCP4.5 and RCP8.5) to forecast future climatic characteristics of PV power potential in Iraq. Insolation is assumed to rise to 4.5 W/m^2 by 2100 in the RCP4.5 scenario, while insolation will rise to 8.5 W/m^2 in the RCP8.5 scenario, which is the worst-case scenario.

5.1. Future atmospheric temperature in Iraq

In this section, future climatic characteristics of atmospheric temperature in Iraq are investigated to explore how their implications could affect PV production in various Iraqi governorates. The values of annual atmospheric temperatures in Iraq are predicted for four future projection periods (2020–2040, 2041–2060, 2061–2080, and 2081–2100) depending on the aforementioned climate scenarios. Fig. 2 depicts an

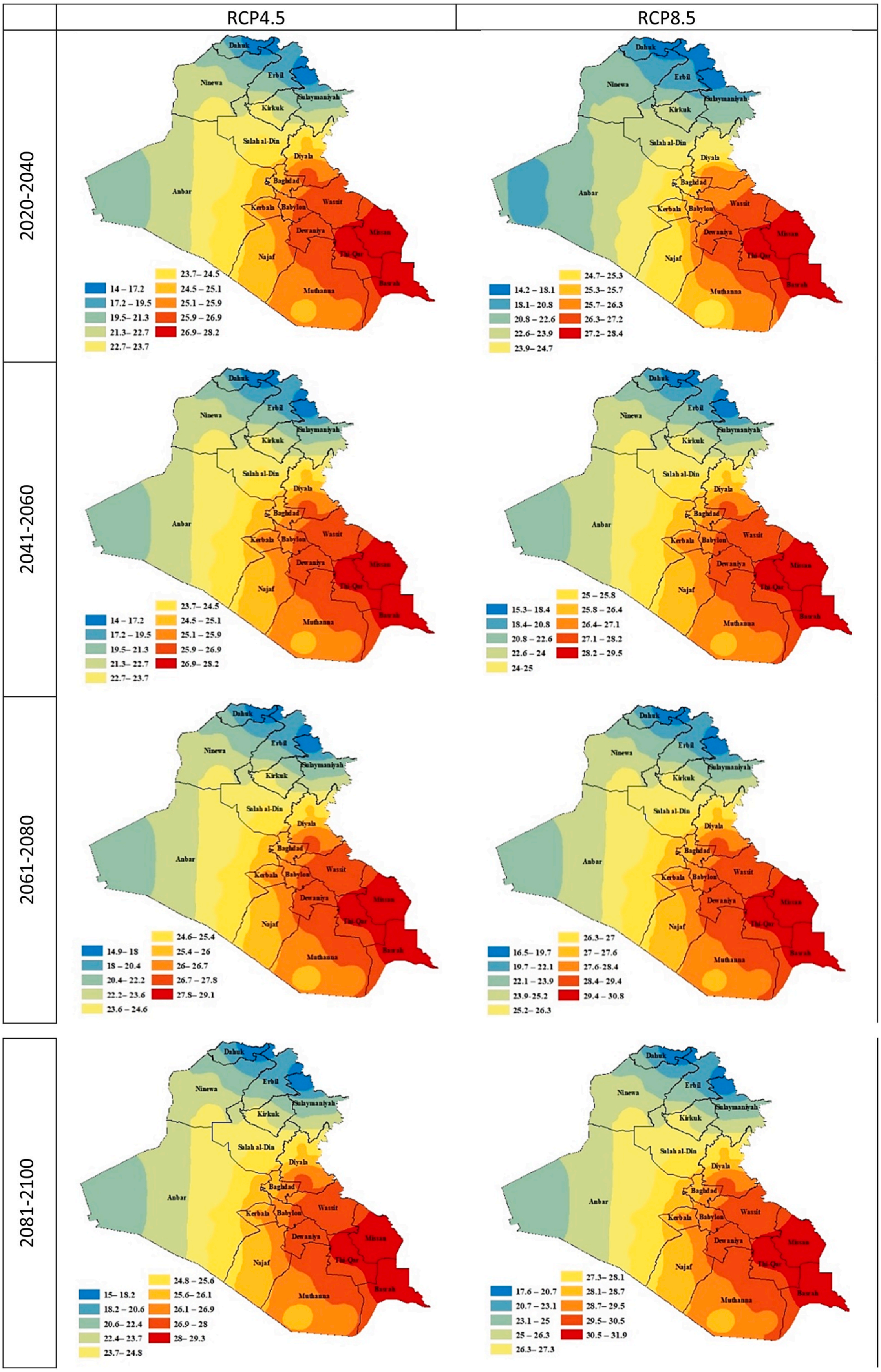

Fig. 2. Projected annual average changes in atmospheric temperature (K) for the periods of 2020–2040, 2041–2060, 2061–2080, and 2081–2100 based on the climate models RCP4.5 and RCP8.5.

analysis of the predicted changes in average atmospheric temperature at the geographical and temporal scale across the different sub-regions of Iraq based on RCP4.5 and RCP8.5 model predictions. As previously reported by Abdaki et al. [27], the average temperature across the country is anticipated to rise by up to 1.3 °C under RCP4.5 and 2.5 °C under RCP8.5 by the end of this century. The data from Fig. 2 indicates that the average temperature increase of around 1.4 °C are expected in Iraq between 2020 and 2040 under RCP4.5 and RCP8.5, respectively. RCP4.5 projects an average rise in temperature of 1.5 °C between 2061 and 2080, while RCP8.5 projects an average increase of 2.4 °C throughout the country. Under all scenarios and for all time periods, the temperature in Iraqi sub-regions (Fig. 2) rises all over the country. These projections are consistent with the findings from other studies for the southern and southwestern regions of Iraq. For example, Hashim et al. [39] projected a temperature increase between 1.2 °C and 2.4 °C in the southern and southwestern regions of Iraq by 2099.

5.1.1. Projected temperature for low emission scenario (RCP4.5)

For atmospheric temperature, median trends show a distinct warming in Iraqi governorates for the period (2020–2100) as predicted by the RCP 4.5 climate model. For the first period (2020–2040), the highest average temperature is projected in the southern and southeastern governorates, particularly in Basra, Missan, and Thi-Qar. The overall temperature range in these regions is 26–28 °C, and the lowest temperatures are recorded in the northern governorates, where they are projected to be 14–17 °C. Moderate averaged temperatures are recorded in the middle and northeastern parts ranging between 22.3 and 25.1 °C. During the second period (2041–2060), the greatest average temperature is projected in the southern and middle governorates, where it varies between 26.5 and 28.8 °C. Meanwhile, the lowest temperatures are anticipated to record in the northern governorates varying between 15.7 and 17.6 °C. Also, during the period (2061–2080), the temperature continues to record high readings in southern region between 27.8 and 29 °C, and the lowest temperature in the north regions, between 14.9 and 18 °C. Finally, during the years (2081–2100), values of the highest average temperature continue to rise between 28 and 29.3 °C in the southern and central governorates. The lowest temperature in the north provinces is projected during the same period to be between 15 and 18.2 °C.

5.1.2. Projected temperature for high emission scenario (RCP8.5)

Similar to RCP 4.5, RCP 8.5 also confirm that median trends of atmospheric temperature will experience significant warming over the period (2020–2100). Between 2020 and 2040, the southern and middle governorates, particularly Basra, Missan, and Thi-Qar, witness the highest average temperatures. The temperature ranges between 27.2 and 28.4 °C in various locations, with the lowest temperatures are recorded in the northern governorates from 14.2 to 18.1 °C. Additionally, the southern and middle governorates are anticipated to have the highest average temperature between 2041 and 2060, ranging between 28.2 and 29.5 °C. Meanwhile, the northern governorates are expected to record the coldest temperatures on record, ranging between 15.3 and 18.4 °C. Additionally, between 2061 and 2080, the temperature continued to record higher in the southern region between 29.4 and 30.8 °C, and relatively lower in the northern regions between 16.5 and 19.7 °C. Finally, during the years (2081–2100), the greatest average temperature values in the southern and central governorates continue to rise between 30.5 and 31.9 °C. The lowest temperature in the north provinces is expected to be between 17.6 and 20.7 °C throughout the same period.

5.2. Future insolation patterns in Iraq

This section examines the annual mean insolation over Iraq from 2020 to 2100 under two different emission scenarios, RCP4.5 and RCP8.5. Four sequencing periods have been chosen for the case study (2020–2040, 2041–2060, 2061–2080, and 2081–2100), each of which is addressed and represented in Fig. 3 by one of the two RCPs used. Additionally, each map in Fig. 3 depicts the mean of 12 months in W/m^2 for the years studied. By the end of this century, the annual mean insolation over the country is expected to increase from 237.6 to 239.3 W/m^2 under RCP4.5 and from 238.1 to 238.7 W/m^2 under RCP8.5. Between 2020 and 2040, an average drop of roughly 1.8 W/m^2 is projected under RCP4.5 (238.8–236) W/m^2, whereas an increase of (234.9–236.1) W/m^2 is expected under RCP8.5. Between 2061 and 2080, RCP4.5 estimates an average increase in insolation of (236.2–238.5) W/m^2, whereas RCP8.5 projects no significant change in insolation (238.9–238.5) W/m^2. As a result, the insolation in Iraq's sub-regions (Fig. 3) swings between some rises and declines depending on the emission scenario and projected time period.

5.2.1. Projected insolation for low emission scenario (RCP4.5)

The median trends in Fig. 3 show a distinct insolation variation in Iraqi governorates for the period (2020–2100) as predicted by the RCP 4.5 climate model. For the first period (2020–2040), the highest average insolation is projected in the western and southwestern governorates, particularly in Anbar, Najaf, and Muthanna. The overall insolation range in these regions is 244.3–250.9 W/m^2, and the lowest insolation values are recorded in the northern governorates, where they are projected to be 224.6–228.1 W/m^2. Moderate averaged temperatures are recorded in the middle governorates ranging between 231.1 and 239.6 W/m^2. During the second period (2041–2060), the highest average insolation is projected in the western and southern parts, where it varies between 245.2 and 250.8 W/m^2. Meanwhile, the lowest insolation levels are anticipated to record in the northern governorates varying between 225 and 231.7. Also, during the period (2061–2080), the insolation continues to record high readings in the western parts between 245.8 and 252.3 W/m^2, and the lowest is between 226.2 and 232.7 W/m^2 in the north region. Finally, during the years (2081–2100), values of the highest insolation continue to rise between 245.7 and 252.2 W/m^2 in the western parts. The lowest insolation in the north is projected to remain almost unchanged during the same period to be between 226.2 and 232 W/m^2.

5.2.2. Projected insolation for high emission scenario (RCP8.5)

RCP 8.5 confirms to somewhat the projections of RCP 4.5 regarding the expected increases in insolation during the targeted timeframe (2020–2100). Values of insolation in the western and southwestern governorates, notably Anbar, Najaf, and Muthanna, will be the highest between 2020 and 2040, according to the RCP8.5 projections. The insolation varies between 243.5 and 250.1 W/m^2 in different parts of the country, with the lowest insolation values are reported in the northern governorates, ranging from 223.5 to 227.1 W/m^2. Additionally, between 2041 and 2060, the western governorates are expected to have the highest average insolation, with values ranging between 244.7 and 251.3 W/m^2. Meanwhile, insolation in the northern governorates is forecast to be the lowest on record, with values ranging between 225.5 and 232.1 W/m^2. For the period between 2061 and 2080, the insolation level remains to be higher in the western parts, between 244.8 and 251.4 W/m^2, and considerably lower in the middle governorates, between 238.2 and 244.8 W/m^2 throughout this time period. The highest average insolation in the southern governorates is expected to continue to rise between 227.0 and 232.5 W/m^2 for the years 2021–2100. During the same time period, the lowest insolation in the northern provinces is forecast to range between 228.4 and 232.6 W/m^2.

5.3. Future PV potential in Iraq

The PV annual productivity, which is defined as the ratio between the projected power capacity and the nominal power capacity, is determined for each area unit of land in the domain and is used to compute the total PV potential. The geographical distribution of the PV

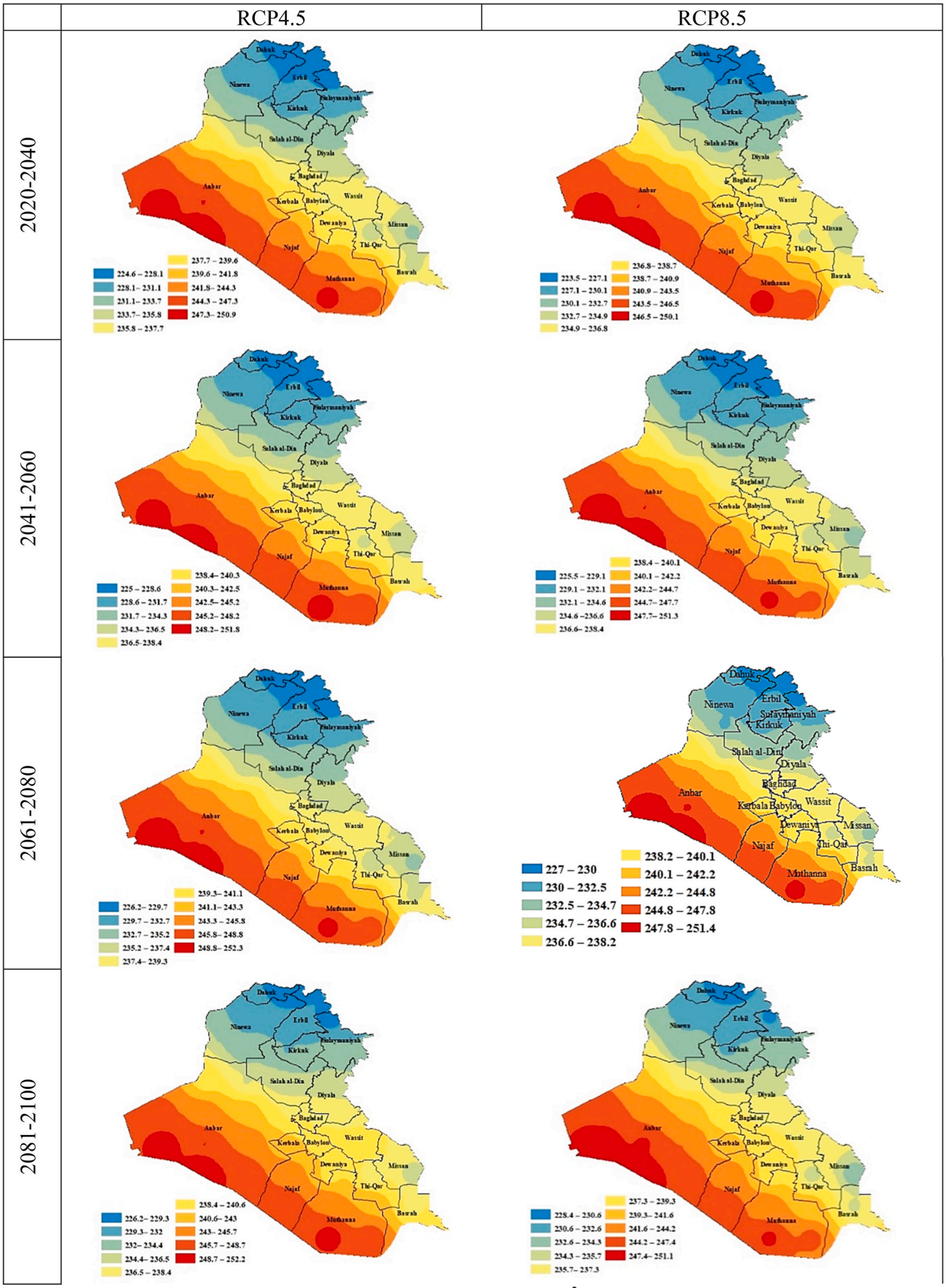

Fig. 3. Projected Annual Average changes in insolation (W/m^2) for the periods of 2020–2040, 2041–2060, 2061–2080, and 2081–2100 based on the climate models RCP4.5 and RCP8.5.

potential is largely explained by the pattern of change in insolation projected by RCP4.5 and RCP8.5, which in itself is closely related to the evolution of PV temperature. PV potential under variable conditions of atmospheric temperature and insolation are presented in Fig. 4 as yearly averaged values over a twenty-year period. The findings of the relative changes averaged by region are presented in Fig. 4. By the end of this century, the annual mean PV productivity across the country is expected to change in the range of −0.3 to 8.1% under RCP4.5 while it is in the

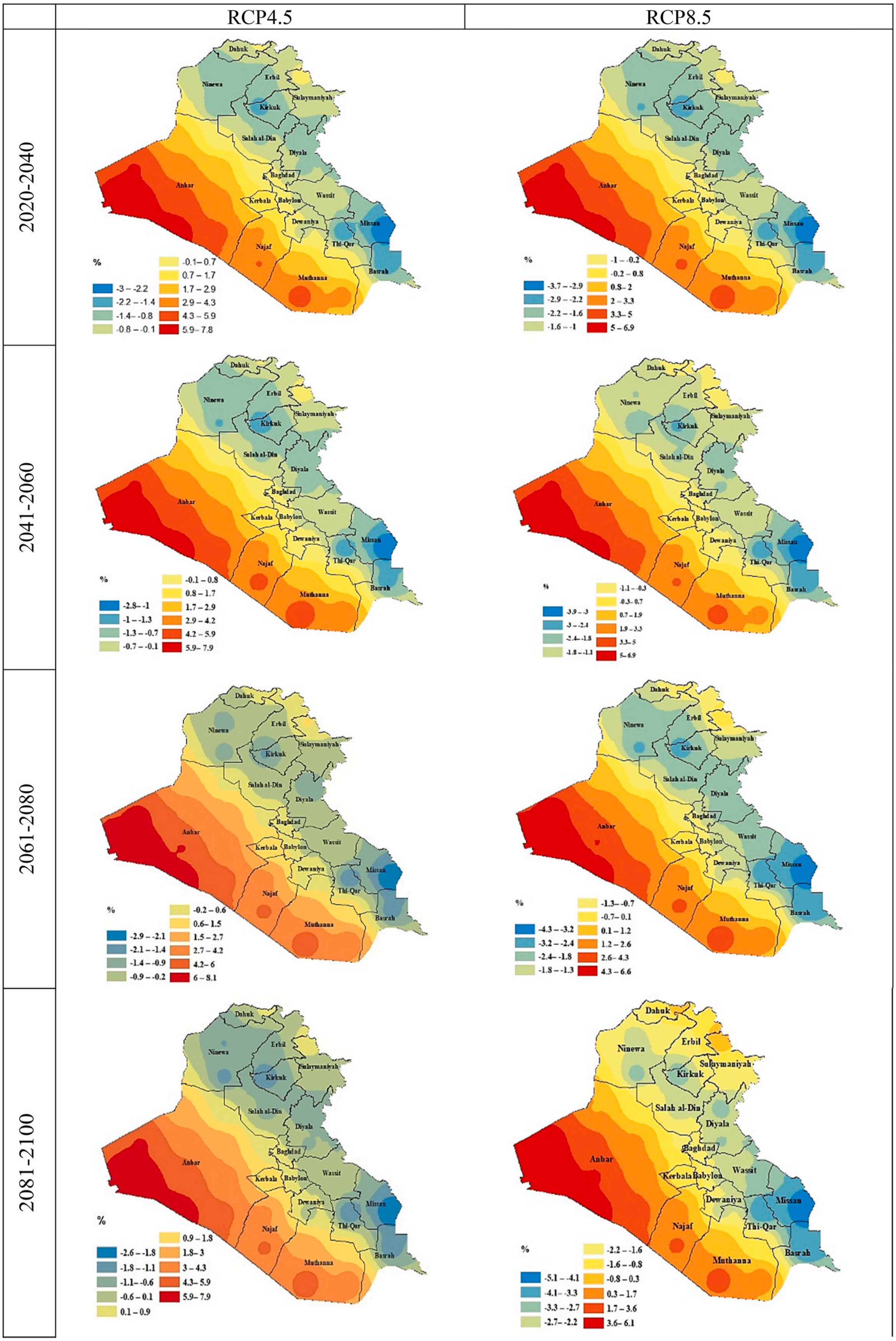

Fig. 4. Projected percentage changes in the PV power potential for the periods of 2020–2040, 2041–2060, 2061–2080, and 2081–2100 based on the climate models RCP4.5 and RCP8.5.

range of −5.1 to 6.3% under RCP8.5. These estimations would be consistent with the projections of Tahir [40], who expected a 8% decline in the PV energy production by 2080 in Qatar, which is also a middle-eastern country with a semi-arid climate. Between 2020 and 2040, an average increase of roughly 3.2% is projected under RCP4.5, whereas an average decrease of −1.3% is expected under RCP8.5. Between 2061 and 2080, RCP4.5 estimates an average increase in PV potential of 2.1, whereas RCP8.5 projects a decline in PV potential of −3.8%. As a result, the PV potential in Iraq's sub-regions (Fig. 4) swings between some rises and declines depending on the emission scenario and projected time period. The most important result is that the PV potential change is positive for RCP4.5 for the major period, while RCP8.5 give the positive signal only for the first period (2020–2040).

5.3.1. PV potentials for low emission scenario (RCP4.5)

Following the median trends shown in Fig. 4, a distinct PV-potential variation is observed in Iraqi governorates for the period (2020–2100), as predicted by the climate model RCP4.5. For the first duration (2020–2040), the western and southwestern regions of the country, particularly Anbar, Najaf, and Muthanna, are expected to have the highest photovoltaic potential. The overall potential range in these regions is 4.3–7.9%, with the lowest values being recorded in the provinces of Thiqar, Missan, and Basrah. They are projected to be between −3 and −1.4%. Other governorates have averaged potentials that range between −0.1 and 2.9%, which are considered moderate by the same standards. In the second period (2041–2060), there are no significant changes in the PV potential distribution because the highest values are still recorded in the western and southwestern parts of the country, where they range between 5.9 and 7.9%. Meanwhile, the lowest potential levels are expected to be recorded in the southeastern governorates, with values ranging between −2.8 and −1.3%. PV potential continues to be lowest in the southeastern parts of Missan, Thiqar, and Basrah between −2.9 and −1.4% during the period (2061–2080), and highest in the western region between 6 and 8.1% during the same period. At long last, during the years (2081–2100), values of the highest potential will continue to rise between 5.9 and 7.9% in the western portions of the country. The lowest potential in the southeastern regions is expected to remain almost unchanged over the same time period, ranging between −2.6 and −1.1%, according to the RCP4.5 projections.

5.3.2. PV potentials for high emission scenario (RCP8.5)

RCP8.5 results confirms to a certain extent that the projections by RCP4.5 for the regions that will experience increases in PV potential during the time period under consideration (2020–2100). According to the RCP8.5 projections, the highest values of solar PV potential will be found in the western and southwestern governorates, particularly in Anbar, Najaf, and Muthanna, between 2020 and 2040. While the potential swings across the country, it is generally between −5.1 and 2.4%, with the lowest potential reported in the northern and southeastern governorates, where it is between 3.6 and 6.9%, respectively. The western governorates are expected to have the highest average PV potential between 2041 and 2060, with values ranging between 5 and 6.9% between 2041 and 2060, according to the RCP8.5 model projections. The PV potential in the southeastern governorates of Missan, Basrah and Thiqar, on the other hand, is expected to be the lowest on record, with values ranging between −3.9 and −2.4%. Throughout the time period 2061–2080, the PV potential in the western parts of the country remains higher, ranging between 4.63 and 6.3%, and significantly lower in the rest of the country, ranging between −4.3 and 4.3%. The average potential in the western governorates is expected to continue to rise between 3.6 and 6.1% for the years 2081–2100, with the highest average potential in the eastern governorates. During the same time period, the lowest potential in the southwestern provinces is expected to range between −5.1 and −3.3% depending on their location.

6. Conclusions

The projections of atmospheric temperature and insolation from two RCP projection models were analyzed for their contribution to the PV modules' output change, over Iraq. The analysis was carried out for four time series: 2020–2040, 2041–2060, 2061–2080, and 2081–2100, with the period 2000–2020 serving as a reference point. The major conclusions from this study are:

1. The analysis reveals that the average temperature across the country is anticipated to rise by up to 1.5 and 2.4 °C under RCP4.5 and RCP8.5, respectively by the end of this century. RCP4.5 predicts a 1.4 °C average temperature rise by the mid-century, while RCP8.5 predicts a 1.8 °C rise during the same time period. Under both scenarios and for all time periods, the temperature in Iraqi sub-regions is projected to rise all over the country.
2. The annual mean insolation over the country is expected to increase from 237.6 to 239.3 W/m^2 under RCP4.5 and from 238.1 to 238.7 W/m^2 under RCP8.5 by the end of this century. Between 2020 and 2040, an average drop of roughly 1.8 W/m^2 is projected under RCP4.5, whereas an increase of 0.6 W/m^2 is expected under RCP8.5. During other periods (2041–2100), RCP4.5 estimates an average increase in insolation to be from 245.7 to 252.2 W/m^2 in the western parts. Meanwhile, insolation in the northern parts is projected to remain almost the lowest in the country during the same period, at between 226.2 and 232 W/m^2. While RCP8.5 projects no significant change in insolation during the same period.
3. The parametric analysis of the contribution of solar insolation and temperature to the future PV potentials, the RCP8.5 scenario predicts a drop owing to the atmospheric temperature increase, which is offset by a relative decrease in insolation, resulting in an overall minor impact on PV productivity. Therefore, the PV potential in Iraqi sub-regions swings between some rises and declines depending on the emission scenario and projected time period.
4. By the end of this century, the annual mean PV productivity across the country is expected to change in the range of −0.3 to 8.1% under RCP4.5 while it is in the range of −5.1 to 6.3% under RCP8.5. More important, the analysis reveals that the PV potential change is positive for RCP4.5 for the major period during the 21st century, while RCP8.5 gives a positive signal only for the first period (2020–2040).

With using the most up-to-date climatic projections for surface insolation and temperature, this study can serve as a first step in investment planning, process optimization, and future energy yield assessment of PV modules in Iraq. However, it is recommended to examine the impacts of other climatic parameters, such as average humidity and precipitation, so as to better predict local-scale variation in solar PV potentials.

Authors contributions

Conceptualization, A.A.F.; methodology, M.S.G.; software, M.S.G.; validation, A.A.F.; investigation, A.A.F. and M.S.G.; writing—original draft preparation, M.S.G.; writing—review and editing, A.A.F.; supervision, A.A.F. All authors have read and agreed to the final version of the manuscript.

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Data availability

Data will be made available on reasonable request.

CRediT authorship contribution statement

Marrwa S. Ghanim: Methodology, Software, Investigation, Writing – original draft, preparation. **Ammar A. Farhan:** Conceptualization, Validation, Supervision, 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.

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