GIS-based multiregional potential evaluation and strategies selection framework for various renewable energy sources: a case study of eastern coastal regions of China

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Abstract

Evaluation of available potential and suitable alternative options for various renewable energy sources (RES) requires the explicit consideration of inter-regional disparities and site-specific conditions (e.g., environmental, socio-economic, and resources features) for a larger scale region or country. This paper presents a novel multiregional analytical framework considering inter-regional suitability difference and inter-RES competitiveness at a given location in order to support efficient and sustainable RES spatial planning strategies. A GIS-based multicriteria evaluation technique was used to identify the geospatial potential/appropriate sites for various RES through combination of satellite-derived information, reanalysis data, ground measurements, and statistical data. The composite index (CI) considering location suitability and sustainability of renewable energy technology was then used to compare different RES options, and as a selection criteria to define suitable strategies for each specific region. A real case study concerning the China’s eastern coastal 10 provinces of RES planning issue demonstrates the applicability of the proposed approach. The present results illustrate how to coordinate the competing relationships between inter-regions and inter-RES for a given location in the eastern coastal regions of China. This could provide useful insight into plan the long-term RES developing paths and facilitate the determination of optimal energy mix for the other same type area.

Introduction

Increasing the proportion of renewable energy power has been a consensus of the international community to mitigate global climate change and get rid of energy dependence on traditional fossil fuels. For the past three decades, China has experienced spectacular economic growth, and successively become the largest carbon emitter since 2007, the largest energy consumer since 2009 [1]. However, since China’s energy mix is dominated by coal which accounted for 66.2% of its primary energy consumption in 2012 and cannot be substantially changed in the near future, the control of carbon emissions will be rather difficult [2]. These present key challenges to China to balance between rising energy demands and potential environmental issues [3].

China’s eastern coastal region is one of the main engine for country’s economic development, especially after the reform and opening-up in 1978, which account for 13% of total area, but carried on 40% of population, and contributed about 60% of GDP [4]. With rapid economic growth and population agglomeration in this region, eastern coastal zone is also in the forefront of energy consumption, while having limited fossil fuels resources. Most of provinces along the coastal lines are currently heavily depending on energy import, such as west-east electricity transmission project, importing liquefied natural gas and raw coal from east and south-east Asia countries. In such
a case, clean energy sources like renewable energy sources and nuclear energy are becoming potential and safety solution for eastern developed provinces to ensure the security of energy supply and reduce CO₂ emissions. Some of developed provinces have made reasonable development goals of renewable energy sources in their medium- and long-term energy development planning to promote the exploitation of clean energy. But there is still lack of adequate feasibility studies about clean energy development in such region.

Due to spatial and temporal variability in renewable energy sources, the development of renewable energy projects requires a thorough analysis of land use issues and lots of constraints [5]. GIS-based analyses have been used to evaluate different categories of renewable energy sources at various research scale, such as global [6, 7], national [8–13], regional and local scales [14–19]. The majority of such applications focus on potential assessment, environmental and ecological impacts, and preferable locations selection. Aydin et al. [17] suggested identification of preferable locations for renewable energy systems is a decision-making problem that requires evaluation of the potential of the resource together with economic and environmental limitations. Spatial multicriteria evaluation (MCE) integrated with GIS allows incorporation of the geographical data with the decision makers’ preferences in order to provide overall assessment of multiple, conflicting, and incommensurate criteria [20]. Thus, GIS analysis might aid to determine appropriate zones according to specific criteria for future development [21].

The purpose of this study was to propose an integrated analytic framework for determine suitable utility technology and optimal site selection at the multiregional level. In this study, the structure of energy consumption and supply for eastern coastal regions of China were reviewed firstly; Furthermore, the large-scale exploitation potential of main categories of RES (i.e., offshore wind, onshore wind, larger scale PV, and biomass energy) and their contributions to regional energy system were estimated using GIS-based MCE method with respect to geographical and technical constrains; Subsequently, we introduced the appropriate development strategies for each coastal regions from a spatial planning perspectives. These present may help build a macroscopical vision for sustainable energy systems based on spatially explicit information.

**Study Area and Datasets**

**Study area**

The target region of this study consists of 10 provinces/municipalities along east coastal regions of China, including Liaoning, Jingjinji (taking Hebei, Beijing, and Tianjin as one region), Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan province (Fig. 1), which is the most developed part in China with the highest population density, large amount of GDP, and huge amount of energy consumption. This region is the forefront of reform and opening up in China, with total area of 129.4 × 104 km² (about 13.5%) and a population of 595.9 million (about 43.5%) in 2010, and contributes to over 54% of total GDP in China. Meanwhile, the amount of energy consumption for eastern coastal regions has been increasing rapidly, from 629.3 Mtoe in 1995 to 2175.2 Mtoe in 2012; the total amount of energy consumption has already cover 60% of that in China in 2012 (Fig. 2). On the other hand, China’s energy import dependency was added up to 9% in 2013, and will reach to 26% in 2020. This trend is more serious for some eastern coastal regions, such as Zhejiang (>90%), Guangdong (>65%), Jiangsu (>90%), etc, which indicates eastern coastal regions will face great challenge of energy supply security for a long time.

Eastern coastal regions of China have limited fossil fuels sources, while have good endowment of renewable energy (e.g., onshore and offshore wind energy, biomass energy). Currently, coastal provinces have focused on development of solar, wind, and biomass energy by taking advantage of favorable geographical locations. Till the end of 2012, the total installed power capacity for wind and solar power generation in this region has, respectively, reached to 26,484.1 MW, and 2763 MW, which accounted for 34.9% and 34.7% of national wind and solar power installed capacity, respectively. As shown in Figure 3, the total amount of wind power installed capacity in Jingjinji, Liaoning, Shandong have dramatically increased, in particular after 2005. Similarly, solar power installed capacity also has experienced a steady growth, whereas the share is still small due to higher generation cost comparison with onshore wind power. Jiangsu, Jingjinji, and Shandong, where endow with good solar energy resources, have larger solar power installed capacity. In addition, biomass power installed capacity is concentrated in eastern coastal provinces of China, and its grid-connection capacity has reached to 3514.84 MW accounting for 45.12% of national total installed capacity at the end of 2013, such as Jiangsu, Shandong, Guangdong, and Zhejiang (Fig. 4). The biomass power generation technology types focus on agriculture and forestry biomass direct combustion and municipal solid waste incineration power. As a whole, wind power has been at a higher development level than the other categories except Guangxi and Hainan provinces, where biomass power have high utility proportion.
Figure 1. Study area of eastern coastal regions of China (Eastern economic zone).

Figure 2. Growth of energy consumption in the study area (1995–2012).
Data sources

To exactly evaluate harnessed potential of regional wind, solar, and biomass energy sources, the study has used the datasets as below:

1. Wind field data: Two surface wind data were used to assess the potential of onshore and offshore wind energy. Ocean surface wind data are derived from spatial blending of high-resolution satellite data (SeaWinds instrument on the QuikSCAT satellite-QSCAT) and global weather center reanalyses (NCEP). The wind field data contain the U and V wind components at a 25 km resolution. The global coverage datasets begin in July 1999 and ends in July 2009 [23]. The dataset was produced using improved Geophysical Model Function (GMF). The WindSat retrievals are believed to be accurate for winds up to at least 30 m/sec. Land surface wind speed data were derived through the School of Geography Oxford (http://www.geog.ox.ac.uk). New et al. [24] constructed a 1° latitude/longitude dataset of mean monthly surface climate over global land areas, which includes eight climate elements: precipitation, wet-day frequency,
temperature, diurnal temperature range, relative humidity, sunshine duration, ground frost frequency, and wind speed, and was interpolated from a dataset of station means for the period centered on 1961 to 1990.

2. Bathymetric data: The bathymetric data of eastern ocean of China are retrieved from the National Geophysical Data Center by the National Oceanic Atmospheric Administration (NOAA) (http://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1/).

3. Solar radiation data: Solar radiation at latitude tilt in China was derived from GIS data of Solar and Wind Energy Resource Assessment (SWERA), which was developed by the National Renewable Energy Laboratory for the U.S. Department of Energy. This data provide monthly average and annual average daily total solar resource averaged over surface cells of approximately 40 km by 40 km in size [25].

4. Land use/land cover data: Multi-temporal Landsat images (Landsat TM/ETM+) were used to produce land use/land cover map in the study area. The high-resolution Google Earth imageries were used as auxiliary information to improve the accuracy.

5. Net primary production (NPP) data: Annual MODIS17A3 NPP data for 2010 in sinusoidal projection were downloaded tile by tile from the Numerical Terradynamic Simulation Group (NTSG) at the University of Montana (http://hdfeos.net/). MODIS17A3 NPP data are formatted as a HDF EOS (Hierarchical Data Format – Earth Observing System) tile and have a resolution of 1 km.

6. Statistical data: In this study, we mainly consider the five food crop categories including rice, wheat, corn, legume crop and tuber crop, and three oil crops categories including peanut, rapeseed, sesame. Each type of annual crop yield at provincial level can be acquired from China Agricultural Statistical Yearbook 2012. In order to match the crop classes with the land-use dataset, the crops mentioned above are reclassified into two classes: paddy field crops (rice) and dry field crops. The Forest stock data are derived from eighth national forest resources inventory, which provides a source of forest inventory data from 2009 to 2013. The forest biomass includes fuel wood, forestry harvesting residues, wood processing waste, and forest pruning and branches, etc. In this study, only the pruning and tending woody residues are considered. The related conversion parameters used in this study are mainly referenced from Shi et al. [26].

Methodology

A brief schematic of our study to determine the alternative RES solution for multiregion level is presented in Figure 5. First, we collect the required data of evaluating the RES potential, which include satellite-derived information, reanalysis data, ground measurements and statistical data. All available dataset are then processing in GIS to prepare the subsequent analysis. The second step is to identify the multiple constraint criteria for eliminating infeasible sites to various RES development. In this article, a set of technological, economic, social, and environmental criteria is selected. Then the mainstream technologies and evaluation methods of energy production for each RES options are selected, and the GIS procedures are conduced to produce various RES energy potential maps. Entropy-weight method and GIS multicriteria decision analysis are further used to calculate the suitability index for each prefecture level region. In the fourth step, a composite index (CI) considering location suitability and sustainability of renewable energy technologies is then used to compare different RES options, and as a selection criteria to define suitable strategies for each specific region. Finally, the composite decision making information including priority of RES options and optimal location for multiregion is determined through qualitative and quantitative evaluation for supporting energy planning.
Onshore wind energy

To obtain high spatial resolution wind speed surface, land surface wind speed data with a 10° latitude/longitude was firstly interpolated to a grid size of 1 km × 1 km, and then masked by administrative boundary of study area using GIS spatial analysis tools. Since the wind speed changes with altitude due to frictional effects at the surface of the earth, monthly wind data at 10 m height should be adjusted to the hub height of chosen wind turbine model. The power law is used by many wind energy researchers to extrapolate the reference wind speed to the hub height [27], and its basic form as follows:

\[ V = V_0(z/z_h)^\alpha, \]  
\[ (1) \]

where \( V \) is the wind speed at height \( z \), \( V_0 \) is the reference wind speed at the reference height \( z_0 \), and \( \alpha \) is the wind speed power law coefficient, and take a value of 0.28, because the suitable areas of wind farm are always located in terrain uniformly and covered with obstacles 10–20 m, for example, residential suburbs, woodland [28].

The electric energy output of wind turbine depends on local wind regime and characteristics of selected wind turbine, such as rated power of the wind turbine generator, the swept area and the power curve of the turbine. Weibull and Rayleigh distributions are often used to derive the theoretical appearance frequency of wind speed [29]. However, the calculated process of such method is relatively complicated, and it need daily wind speed dataset. For the purpose of this study, we follow the estimation method which is proposed by Hoogwijk [6]. There is a correlation between full-load hours and average wind speed, so the full-load hours could be simplified as a linear function of the average annual wind speed. It is supposed that Repower 5 MW wind turbines are installed in the study area. We build a simple linear regression equation between full-load hours and average annual wind speed using a Weibull distribution and the power curve of Repower at 23 meteorological stations of China’s eastern coastal provinces. The detailed results of this correlation analysis was performed by Ref. [30]. Based on this supposition, the electric energy potential of wind turbine in each grid cell \( E_i \) is estimated by the below formula:

\[ E_i = P_R \cdot H_i \cdot \lambda \]  
\[ (2) \]

In the above equation, \( P_R \) is the power of selected wind turbine [MW], \( H_i \) is the full-load hours [h], and \( \lambda \) represents a conversion factor [0.86].

Not all the land surface are suitable to install wind turbines. In the determination of geographical potential of onshore wind power, some of land use categories, including forest, water bodies, farmland, and built-up area, are excluded. In addition, land with slopes >10° are also excluded, since such areas are difficult to access for heavy machinery to installing and maintaining wind turbines.

Recent studies have shown that for turbines that are spaced 10 rotor diameters, \( D \), apart in the prevailing downwind direction and five rotor diameters apart in the crosswind direction, array losses are typically very low (<10%) [27]. The spacing parameters indicate a spacing factor of about 5 MW/km² if considering a rotor diameter \( D = 90 \) m. As a result, the regional onshore wind energy potential can be estimated with consideration of geographical constrains.

Offshore wind energy

The offshore wind energy potential was calculated using the similar method as onshore wind energy. Ocean surface wind data were interpolated to a grid size of 1 km × 1 km using kriging method, and then masked by administrative boundary of study area using GIS spatial analysis tools. The wind speed at the hub height was linearly interpolated from 10 m height through power law of wind profile, which the wind speed power law coefficient (\( \alpha \)) take a value of 0.1. Water depth is the primary concern to determine the type of foundation. Bottom-mounted foundations have been widely used for the area where water depth is <20 m. For deeper water, floating foundations have to be used. Even with the floating foundation, the area where the water depth is deeper than 200 m is difficult to use due to economical reason [31, 32]. In this study, two scenarios of water depth were assumed: (1) 0–20 m, (2) 20–50 m.

| Category                | Evaluation indicators | Weights for onshore wind | Weights for solar PV | Weights for biomass |
|-------------------------|-----------------------|--------------------------|---------------------|---------------------|
| Social-economic criteria| Per capital GDP (Yuan/person) | 0.0859                  | 0.0887              | 0.1200              |
|                         | Total demand of electricity (kWh) | 0.2054                  | 0.2123              | 0.2871              |
| Resources features      | Available supply potential (GWh/year) | 0.4070                  | 0.4225              | 0.1133              |
|                         | Average energy output density (MWh/km²) | 0.0579                  | 0.0246              | 0.1387              |
| Supporting infrastructure| Road density (km/km²)      | 0.0370                  | 0.0382              | 0.0517              |
|                         | Marginal land area percentage (%) | 0.2069                  | 0.2137              | 0.2891              |
Solar energy

Generally, there are two kinds of application models for solar PV generation: (1) for the suitable area outside of built-up areas, it means for large-scale PV station; (2) for the built-up areas, the roof-top PV is the main system. In this study, we only estimate the potential of large-scale PV system in the study area. The PV production energy is determined by three main parameters, solar radiation of local...
area, and size and performance ratio of PV systems. The annual total amount of PV generation electricity in the grid cell $i$, $E_i$, was calculated using the following equation [33]:
\[
E_i = \frac{P_i G_i \eta_T}{1000 \text{ W/m}^2},
\]
where $P_i$ is the peak power of PV system installed in grid cell $i$, $G_i$ is the annual total amount of global radiation tilted at the latitude in grid cell $i$, $\eta_T$ is the performance ratio of PV system. A typical value for PV system with modules from mono- or polycrystalline is around 0.75.

Based on the previous studies, geographical restriction areas are referred to forest, built-up area, water body, natural reserve, agriculture land, and land with slopes of more than 4°. Additionally, we defined a PV capacity density of 44 MW in each grid cell [34].

**Biomass energy**

Unlike the other renewable energy, biomass is distributed over large areas and biomass productivity varies greatly with site-specified conditions of climate and soil. Thus spatial variations of biomass production are crucial for the estimation of the available potential. In this study, we followed the method applied in the research of Gehrung and Scholz [35]. Based on the assumption that the distribution of biomass available for purposes of electricity generation is influenced directly by biomass increment on hand as net primary productivity, the total amount of each type of biomass production was allocated to the whole regarded land cover weighting with NPP data. The weighted disaggregation methodology is expressed in the following equation:
\[
P_{ij} = P_k \times n^{-1} \times NPP_{ij} \times \text{NPP}^{-1},
\]
where $P_{ij}$ is the amount of biomass production on pixel $i,j$; $P_k$ is the total amount of biomass production at provincial level; $n$ is the number of pixel of regarded land cover; $NPP_{ij}$ is the net primary productivity of pixel $i,j$ in region; $\text{NPP}$ is the average net primary productivity of pixels of regarded land cover in the region.

Then the total amount of annual energy generation for biomass residuals in each 1 km$^2$ pixel can be calculated by using equation as follows:
\[
P_{ij}^T = P_{ij} r_i e_i (1 - s - l) \eta_i,
\]
where $P_{ij}^T$ is the annual energy generation of biomass residues on pixel $i,j$; $P_{ij}$ is the amount of biomass production on pixel $i,j$; The parameter $r_i$ is the fraction of biomass residues which can be used to generate electricity; The parameter $e_i$ is the energy content of biomass residues, the low heating value of 15 MJ/kg was adopted for all the crop types, and 16 MJ/kg for all the forestry residues; The ratio $S$ is the fraction of residues which should be returned to soil for ecological/
environmental reasons, we defined the conservative value of 0.5; The fraction l is the loss coefficient of biomass residues during the collection and transportation process, and the value of 0.05 is taken for all the residues. A $\eta_i$ is the efficiency of the convention biomass to power. For estimation of technical potential, we choose the high efficient power generation system with a convention efficiency of 40% as reference system.

Table 2. The potential of onshore wind energy in the study area.

| Name    | Total area (km²) | Annual average wind energy (MWh/km²) | Min. value of wind energy (MWh/km²) | Max. value of wind energy (MWh/km²) | Suitable area (km²) | Energy Potential (TWh/year) |
|---------|-----------------|--------------------------------------|-------------------------------------|-------------------------------------|---------------------|-----------------------------|
| Liaoning | 145,500         | 10,523                               | 8163                                | 14,771                              | 5853                | 61.4                        |
| Jingjinji| 215,200         | 7300                                 | 3499                                | 11,700                              | 24,940              | 181.4                       |
| Shandong | 153,500         | 10,709                               | 5943                                | 15,586                              | 4439                | 47.3                        |
| Jiangsu  | 101,000         | 7170                                 | 5789                                | 11,455                              | 295                 | 2.0                         |
| Zhejiang | 101,900         | 5485                                 | 4120                                | 7403                                | 1131                | 6.1                         |
| Shanghai | 6254            | 7059                                 | 6195                                | 7722                                | 0                   | 0.0                         |
| Fujian   | 121,700         | 4376                                 | 1255                                | 7665                                | 4740                | 20.6                        |
| Guangdong| 176,700         | 3187                                 | 543                                 | 6595                                | 1253                | 4.0                         |
| Guangxi  | 236,300         | 1556                                 | 359                                 | 3998                                | 6026                | 9.4                         |
| Hainan   | 33,800          | 5495                                 | 4614                                | 6296                                | 316                 | 1.7                         |

Composite index by GIS-based multicriteria evaluation techniques

Location suitability and sustainability index of RES technologies were often used for assessing/comparing the comprehensive performance of various RES systems at the multiple scales. The evaluation of optimal RES alternative options for multiple regions requires the explicit consideration of inter-regional disparities and sustainability performance of
different RES technologies. In this context, we propose a novel composite index (CI) aggregated both location suitability and sustainability of RES technologies using GIS-based multicriteria evaluation techniques. CI can be calculated by the maximum selection method. We can take CI as a qualitative and quantitative evaluation criteria to determine the priority development RES option or optimal energy mix for each subregion. Therefore, the CI can be expressed as follows:

\[
CI_j = \text{Max} \left[ SL_1 \cdot U_{1j}, SL_2 \cdot U_{2j}, SL_3 \cdot U_{3j}, \ldots, SL_n \cdot U_{nj} \right],
\]

where \( CI_j \) is the composite index for district \( j \), \( SL_i \) is the location suitability index of RES type \( i \) (\( i = 1, \ldots, n \)) for district \( j \), \( U_{ij} \) is the sustainability index of RES type \( i \).

The location suitability index (SI) for various RES is introduced to define the priority sites in a larger scale area and produce the final suitability map. A weighted linear combination (WLC) is selected to combine multiple evaluation criteria, and is expressed as follows:

\[
SI_j = \sum_{i=1}^{n} w_i x_{ij},
\]

where \( w_i \) is the relative weight of the evaluation criteria \( i \), and \( x_{ij} \) is the standardize score of district \( j \) for the evaluation criteria \( i \). RES location selection action associated with local infrastructure conditions, social-economic and resources features aspects. In this section, six indicators are selected

**Table 3. Offshore wind energy potential in different water depth.**

| Name     | Total area (km²) | Annual average wind energy density (GWh/km²) | Offshore wind energy potential (TWh/year) |
|----------|------------------|---------------------------------------------|------------------------------------------|
|          | 0-20 m | 20-50 m | 0-20 m | 20-50 m | 0-20 m | 20-50 m |
| Liaoning | 23,764  | 22,001  | 21.3   | 20.7    | 506.9  | 441.2   |
| Jingjinji| 10,230  | 13,093  | 20.2   | 20.1    | 206.2  | 263.7   |
| Shandong | 33,029  | 56,589  | 20.1   | 20.2    | 664.8  | 1149.9  |
| Jiangsu  | 38,635  | 57,134  | 20.9   | 21.6    | 807.2  | 1265.5  |
| Zhejiang | 24,579  | 19,544  | 26.5   | 26.5    | 651.6  | 519.6   |
| Shanghai | 10,357  | 23,109  | 26.1   | 25.2    | 270.6  | 572.4   |
| Fujian   | 11,608  | 42,596  | 31.9   | 30.9    | 369.8  | 1306.1  |
| Guangdong| 26,848  | 53,045  | 24.4   | 25.3    | 655.7  | 1368.3  |
| Guangxi  | 6410    | 11,240  | 21.6   | 22.0    | 138.8  | 250.1   |
| Hainan   | –      | 19,388  | –      | 23.1    | –      | 448.8   |
aiming to evaluate the location suitability of each region (Table 1). The entropy-weight method is used to calculate the weights of each criteria for onshore wind, solar PV, and biomass energy. If there is a large difference between the objects for a criterion determined, this criterion can be regarded as an important factor for the analysis of alternatives [36]. Offshore wind is not considered in this evaluation process because of its location specificity. In equation (6), UI is another key factor for evaluating the sustainability of different RES technologies, and there is a range of important criteria that needs to be considered. Troldborg et al. [37] provided a ranking of the RES technology with MCA by selecting criteria and gathered information from extensive literature reviews. We assign directly a fixed criteria value as the UI value for each RES type in this study based on the ranking order of Troldborg’s paper (Fig. 6). As all above evaluation procedure, the priority RES alternative map was finally produced, and it can offer a comprehensive decision making information on optimal RES alternative solution for each district in the study area.

Results and Discussion

In this section, the results of onshore wind energy, offshore wind energy, solar PV, as well as biomass energy potential of each eastern coastal regions considering

![Figure 11. Spatial distribution of annual solar radiation for the study area (kWh/m²).](image-url)
geographical and technical restrictions are presented and discussed.

**Onshore wind energy**

Onshore wind power is one of the most promising GHG mitigation technologies with huge resource availability and a large deployment rate. The spatial distribution of annual wind speed and electricity output in each grid cell through eastern coastal regions is shown in Figure 7. At 100 m height, annual wind speed of the land surface varied greatly over the region from 3 to 9 m/sec. It can be seen that the provinces around Bohai rim like Liaoning, Shandong, Hebei, have the highest wind energy resources. Meanwhile, the coastal zones in the eastern and southern China are also endowed with excellent wind energy resources (i.e., Yangtze Delta region, Zhejiang, Fujian, Guangdong; see Fig. 7 left). Figure 8 shows the monthly average wind speed in each coastal region. There is a marked seasonal variation in average wind speed, for most of regions higher in spring-winter months and lower in summer-autumn months due to the typical monsoon climate. It can be seen that monthly wind speed is the highest in April (5.58 m/sec) and lowest in August (4.57 m/sec).

In addition, the spatial pattern of wind power output for the study area is similar to that of wind speed (see Fig. 7 right). On the base of primary estimation results, annual wind power output differs in value over the region from 300 to 15,600 MWh/km². The total wind energy potential in the study area is up to 7590 TWh/year, while after considering the geographical restrictions, it is reduced to 334 TWh/year. As shown in Table 2, the northern

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**Table 4. The potential of solar energy in the study area.**

| Name     | Total suitable areas (km²) | Min. value of solar energy density (TWh/km²) | Max. value of solar energy density (TWh/km²) | Mean value of solar energy density (TWh/km²) | Solar energy potential (TWh/year) |
|----------|----------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|----------------------------------|
| Liaoning | 2310                       | 52.1                                        | 66.8                                        | 60.7                                        | 140.2                            |
| Jingjinji| 8907                       | 52.9                                        | 71.7                                        | 63.9                                        | 569.4                            |
| Shandong | 1421                       | 52.0                                        | 56.9                                        | 54.6                                        | 77.6                             |
| Jiangsu  | 172                        | 51.2                                        | 55.7                                        | 52.8                                        | 9.1                              |
| Zhejiang | 588                        | 48.0                                        | 54.3                                        | 51.9                                        | 30.5                             |
| Shanghai | –                          | 49.2                                        | 53.7                                        | 52.3                                        | –                                |
| Shanghai | –                          | 44.0                                        | 55.7                                        | 51.9                                        | 69.0                             |
| Guangdong| 495                        | 49.2                                        | 55.6                                        | 52.0                                        | 25.8                             |
| Guangxi  | 1963                       | 46.2                                        | 54.9                                        | 50.2                                        | 98.5                             |
| Hainan   | 161                        | 52.8                                        | 62.0                                        | 58.2                                        | 9.4                              |
part of coastal region (i.e., Jingjinji, Liaoning, Shandong) had higher wind energy potential due to the larger amount of suitable installed areas. Correspondingly, the eastern and southern parts of China had lower onshore wind energy potential. For example, the onshore wind energy potential for metropolis Shanghai is almost zero, since there is no suitable areas to install wind turbine with the process of urban sprawl and population agglomeration.

**Offshore wind energy**

The distribution of offshore wind speed in east coastal zone is shown in Figure 9. The highest annual wind speed is found in the coast of Fujian due to the funnel effect of Taiwan Strait. The northern Guangdong and southern Zhejiang are also endowed with good wind resources compared with the other coastal areas. It is essential to demonstrate the seasonal variation in wind speed, which has a significant impact on the electricity supply and adjustment. Figure 10 shows the monthly average wind speed profile in each coastal area. As shown in the data, the minimum monthly average wind speed appeared in summer months (5.8 m/sec), and the maximum in winter (8.3 m/sec). In general, higher wind speed variation located in the coast of Fujian, Zhejiang, and Guangdong.
To get a more comprehensive understanding of offshore wind energy potential, the total annual power generation at different locations are presented in Table 3. Overall, the offshore wind energy potential in the water depth of 0~20 m and 20~50 m can reach to 4271.5 TWh/year and 7585.6 TWh/year, respectively. For the shallow water zones with the depth of 0~20 m, the higher potential is located in Jiangsu, Shandong, Guangdong, and Zhejiang, which have longer coastline. For the deeper water zones with the depth of 20~50 m, Guangdong, Fujian, and Jiangsu have good offshore wind resources. Spatial patterns of offshore wind energy potential in Hong’s study [32] are consistent with our results. Currently, offshore wind energy in shallow waters with depths of 0~20 m are viable due to technically mature and economically feasibility. As a result, onshore and offshore wind energy are shown a complementary effect from the point view of spatio-temporal dimension.

### Solar energy potential

Regional solar energy resources are related to latitude, terrain, and local climatic conditions. Figure 11 shows that the annual solar radiation differs in value over coastal region from 1312~2175 kWh/m² and 7585.6 TWh/year, respectively. For the shallow water zones with the depth of 0~20 m, the higher potential is located in Jiangsu, Shandong, Guangdong, and Zhejiang, which have longer coastline. For the deeper water zones with the depth of 20~50 m, Guangdong, Fujian, and Jiangsu have good offshore wind resources. Spatial patterns of offshore wind energy potential in Hong’s study [32] are consistent with our results. Currently, offshore wind energy in shallow waters with depths of 0~20 m are viable due to technically mature and economically feasibility. As a result, onshore and offshore wind energy are shown a complementary effect from the point view of spatio-temporal dimension.

### Solar energy potential

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large-scale PV is the largest in Jingjinji, which has a larger amount of grassland and flat ground. However, several developed regions like Jiangsu, Zhejiang, Guangdong, and Shanghai have limited available areas to install PV station. Thus, Jingjinji and Liaoning have larger solar energy potential (accounting for about 70% of total mount) compared with other coastal regions. Overall, the potential of large-scale PV in eastern region reaches to 1029.5 TWh/year.

**Biomass energy potential**

To get a spatial explicit result of biomass residues, the spatial allocation of available agricultural crop and forest pruning residues amount was conducted with spatial analysis tools. In Figure 13, the total amount of biomass residues energy density in 50 km × 50 km supply regions are shown. The energy density of biomass residues varies greatly over region in the range between 0 and 684 GWh/year. The hotspot regions are located in major agricultural provinces such as Shandong, Jiangsu, and southern part of Hebei. Some regions of Liaoning also have larger biomass energy potential.

As shown in Table 5, the total amount of agriculture and forestry residues is 102.5 TWh/year for the study area, and the top four regions include Shandong, Jingjinji, Jiangsu, and Liaoning. Moreover, the available amount of dry crops residues is twice more than that of paddy residues. The potential production of four provinces...
occupies more than 70% of total across study area. Due to its superb climate and geographical conditions, it is as major agricultural production regions in China. In addition, plenty of marginal land are also available in such regions. Thus, biomass energy as a stable RES option should be priority exploration in the north part of China.

**Renewable energy development strategies in eastern coastal region**

Location suitability index maps for each RES type were determined by combining entropy-weight method and GIS multicriteria decision analysis in eastern coastal regions of China. In this procedure, we took the prefectural level regions as basic assessment units (a total of 115 subregions). As the results shown in Figure 14, the larger SI for three RES types are all emerged in the Jingjinji, Shandong, Liaoning, Yangtze River Delta and Pearl River Delta Region with about 15% of land coverage. Such areas are suitable to development of RES due to better economic foundation and larger marginal land. It is clearly seen that most of areas in southeastern parts of our country have the lower value of suitability index. The lack of marginal land is the largest constrain factor for these regions.

A ranking procedure was then conducted by a trade-off between SI and UI of different RES options to determine an overall RES alternative solution map. The priority RES technology was chosen according to the value of CI for each prefectural level region (Fig. 15). As the result, about 12% of the study area (including Beijing, part of Hebei and Liaoning) is suitable for solar PV farms, and 35% of the study area (including Shandong, Jiangsu, and part of Liaoning, Hebei) is suitable for biomass farms. The other 53% of the study area is found to be suited for onshore wind development. By optimizing the RES option for each district, the issue of spatial energy planning for multiple regions can be easy to deal with.

Eastern China’s region has shown to be vulnerable to electricity supply and has demanded significant RES development in order to address its challenges. According to official statistics, eastern China’s provinces have been increasing its RES installed generating capacity and had reach to 32.76 GW in 2013. Onshore and offshore wind play an important role in the past decades, and account for 80% of total installed capacity. Total amount of electric consumption for 10 provinces of study area had reach to 2885.13 TWh in 2013. Based on the evaluation of our study, current overall RES generation potential in eastern China is 5737.5 TWh, which is close to twice time of electric consumption in 2013. Considering technical and economic feasibility of RES technologies, onshore and offshore wind will continue to play an important role in future electric supply system of eastern China. Among the main sources of RES options, biomass and solar PV energy offer greater potential as supplementary sources of electric generation. Besides some technical, economic, and policy issues, an integrated spatial coordination and a scientific environmental cognition are two important factors for it. The spatial coordinated development should be implemented according to the spatial disparity and consistency among the major renewable energies, coal resources, energy consumption and its major influencing factors in China [38].

**Conclusions**

This study attempted to propose a new multiregional analytic framework to determine the location suitability and priority RES options for a larger scale region. A case study of this approach was conducted to 10 provinces/municipalities along east coastal regions of China. Overall, the annual potential RES production from wind, PV, and biomass sources was 5737.5 TWh in eastern China’s 10 provinces, which is close to twice times of electric consumption in 2013. Among the main sources of RES options, offshore wind in the water depth of 0–20 m will play an important role in future electric supply, especially for coastal provinces of Fujian, Zhejiang, and Guangdong. Biomass and solar PV energy offer greater potential as supplementary sources of electric generation. Selection of priority development RES technology for specific location was a trade-off procedure between location suitability and sustainability of different RES options. A favorable incentive policy and spatial coordinated development strategy are also essential for achieving higher future targets in terms of electricity supply security and environmental friendly technologies.

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**Conflict of Interest**

The authors declare no conflict of interest.

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