Spatial Aggregation and Renewable Energy Landscape Planning: A Case Study in Victoria

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Abstract: Spatially explicit assessment of renewable energy resources is critical for large scale landscape planning and design aimed at promoting clean energy supply and carbon neutrality so that future economic development and social advancement can be sustained. Renewable energy planning at national or state level is pivotal to a nation's socio-economic sustainability in the context of the oil crisis, anthropogenic climate change and the social and economic impacts of globalisation resulting in the international dispersal of energy supply and ownership. Using Victoria (Australia) as a case study, this study aims to investigate the annual spatial heterogeneity of renewable energy potential across the state towards identifying the strengths and appropriate uses of spatial modelling for regional decision making in energy planning. The research explores spatial distribution of solar radiation and wind energy in Victoria and their potential in enabling 100% clean energy supply at utility and household levels. This study demonstrates the usefulness of integrating spatial analysis in planning for carbon-neutral energy supply. It is also clear that the adoption of spatial modelling systems for renewable energy planning also requires modelling of relevant infrastructure limitations and opportunities inherent in the energy sector. The paper concludes with recommendations for future renewable energy planning as a useful practice for carbon emission reduction and climate change mitigation.

Keywords: Renewable energy, solar and wind power, spatial aggregation

1 Introduction

As the largest per-capita emitter, Australia is charged with responsibility to overcome the negative impacts on the environment and other problems associated with fossil fuels availability and usage, which have forced the country to enquire into and change to environmental friendly alternatives that are renewable to sustain the increasing energy demand (BAHADORI & NWAOHA 2013). Renewable Energy is part of Australia's energy supply matrix with over A$100 billion spent annually on renewable energy projects since 2007 (MARTIN AND RICE 2015). In this context, many studies have been carried out on renewable energy utilisation in Australia, but most of these studies are focused on solar energy (CSIRO 2012, DAVY & TROCCOLI 2012, BAHADORI & NWAOHA 2013, CHEUNG et al. 2015), which may be attributed to the fact that solar energy is one of the highly untapped and underutilized renewable energy sources and Australia has the highest average solar radiation per square metre of any continent in the world (BAHADORI & NWAOHA 2013). However, the various renewable energy sources need to be balanced and their use carefully planned since they are characterized by high temporal and spatial variability that will pose challenges to maintaining a well-balanced supply and to the stability of the grid (BLASCHKE et al. 2013). This research investigates the annual spatial heterogeneity of renewable energy potential across the state of Victoria. The study explores spatial distribution of solar radiation and wind energy in Victoria and their potential in enabling 100% clean energy supply at utility and household levels. Other forms of renewable energy such as biomass, hydro and geothermal or marine are not discussed in this paper due to the discrete nature of their spatial distribution in Victoria.

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2 Spatial Datasets

Given the spatial scale and the range of complexities associated with the study, the following data are collected from various sources (Table 1) for spatially explicit energy modelling using ESRI ArcGIS Desktop 10.5 software package.

Table 1: Input data used for renewable energy spatial aggregation in Victoria

	Datasets	Attributes	Resolution/ Format	Data Source
Solar	Solar radiation	Monthly average	1990-2011, 2 km raster	BOM (Bureau of Meteorology)
Wind	Wind speed	Daily average	1975-2006, 2 km raster	CSIRO Land and Water, 2008 McVicar, 2008
Ancillary datasets	SRTM DEM	–	30 m raster	Geoscience Australia, 2014
	Population density, 2016 Australia Census	Annual	1 km raster	LandScan, 2016; ABS, 2017
	Energy Intensity (Secondary)	Annual	1 km raster	LandScan, 2016; ABS, 2017; CEA, 2016
	National grid	–	Vector data	Geoscience Australia, 2012; 2013

Considering the diverse sources of data collected, some preliminary data processing tasks are performed, e. g. reprojection (for data in different coordinate systems), resampling (for data in different spatial resolution), and cookie-cutting (for data with different spatial extent), so that all input data are normalised into the same GDA VicGrid 94 coordinate system, the same spatial resolution (5km, to facilitate computation while balancing data processing time and spatial resolution) and the same spatial extent (using identical coastline and state boundary in accordance with GEODATA COAST 100K 2004 products by Geoscience Australia). Then the following workflow (Figure 1) is used for further data modelling and analysis. During this process, extra attention is paid to identify the strengths and appropriate uses of spatial modelling for regional decision making in energy planning. The outcomes of the spatial analysis are discussed below.

3 Methods and Results

3.1 Solar Energy Capacity

Solar energy is one of the best renewable energy sources with least negative impacts on the environment (SOLANGI et al. 2011). However, despite it has the highest average solar radiation per square metre in the world, Australia's primary energy consumption of solar energy accounted for only 11.9 % of all renewable energy use and only 0.7 % of primary energy consumption in 2017–18 (DEPARTMENT OF ENVIRONMENTAL AND ENERGY 2018). The outputs from the solar radiation modelling display clear seasonal and spatial variations of solar energy capacity in Victoria (Figure 2), indicating the necessity and opportunity to integrate solar energy with other forms of renewable energy to contribute to a well-balanced energy supply and to the stability of the grid in Victoria.

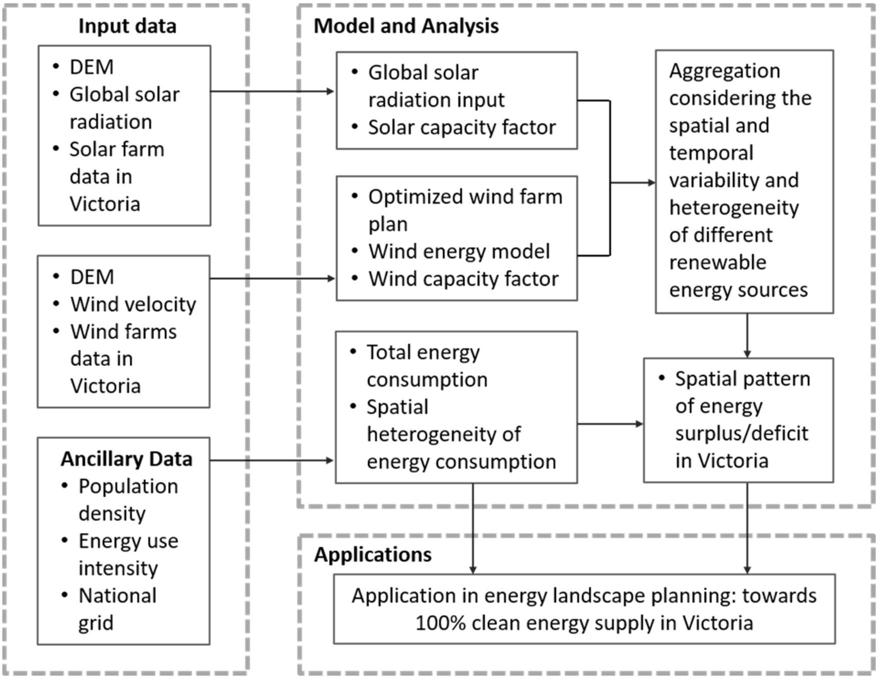

Fig. 1: GIS-based workflow for renewable energy modelling and aggregation for Victoria, Australia

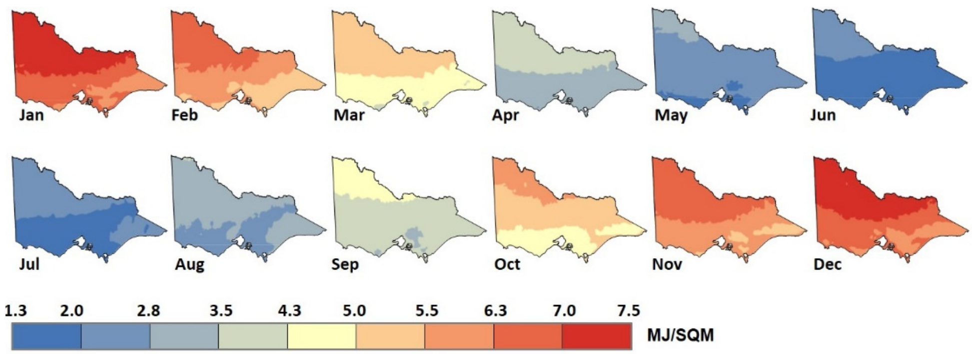

Fig. 2: Solar energy capacity (per m^2 per day) in Victoria (1990-2011 average); based on Capacity Factor = 25 % (DELWP, 2016)

3.2 Wind Energy Capacity

To estimate wind energy, imagine a surface with area A, which is perpendicular to the direction of the wind. The energy content in the wind, flowing with the air with density through an imaginary surface with area *A* during the time *t* can be described by the kinetic energy of the particles in the wind air as follows

$$E_{wind} = ½\, m_{air} \times v^2 = ½\, (\rho_{air} \times A \times v \times t) \times v^2 = ½\, \rho_{air} \times A \times t \times v^3 \quad (1)$$

where E_{wind} is wind energy; m_{air} is the mass of air; v is wind speed (KISSELL 2010); ρ_{air} is the density of air, which varies with the altitude and time, and depends on the temperature and pressure. However, since the variations are very small, average air density at ground level (1.225 kg/m^3) is widely accepted as the air density in the hub height of wind turbines (CARRILLO et al. 2013).

Power is energy per unit time, so the wind power is

$$P_{wind} = E_{wind} / t = ½\, \rho_{air} \times A \times v^3 \quad (2)$$

P_{wind} is total wind energy capacity per second.

Considering *A* (or the blades of a turbine) is often perpendicular to ground, the total maximum possible *A* is calculated using the total land area in Victoria, the rotor diameters, and spacing between wind turbines are used to estimate the wind energy capacity. The outputs from the model display distinct seasonal and spatial variations of solar energy capacity in Victoria (Figure 3).

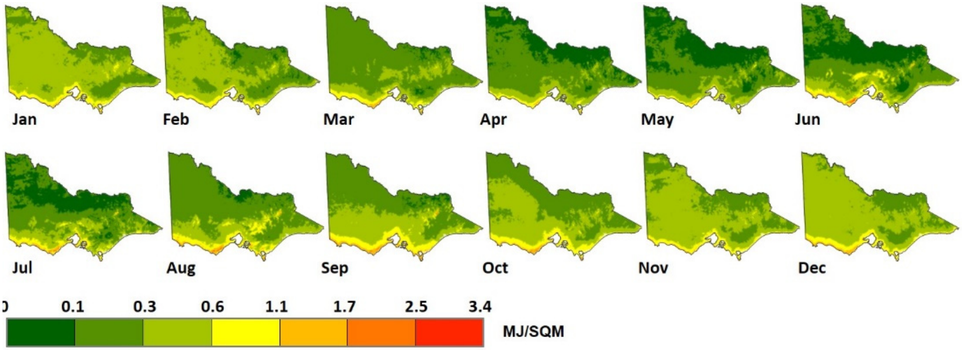

Fig. 3: Total daily wind energy in Victoria (1975-2006 average), based on Capacity Factor = 34 %; rotor diameter = 60 m, spacing between wind turbines perpendicular to wind = 120 m; parallel to wind = 180 m

3.3 Spatial Aggregation of Solar and Wind Energy

Similar to the temporal pattern of solar energy (the hot seasons show the highest energy potential), wind energy pattern indicates highest energy potential in summer time too (Oct – Mar). On the contrary, the spatial pattern displays that solar energy capacity decreases from inland (lower latitude) to coastal areas (higher latitude), while the wind energy potential increases from inland to the coastal areas. The reciprocal spatial distribution pattern indicates opportunities to aggregate solar and wind energy to alleviate the uneven distribution of renewable energy resources in the state, thus reduce the pressure of investing on large scale infrastructure construction which is often necessary for resource redistribution.

The ArcGIS software package provides efficient spatial overlay of the two types of renewable energy sources. Monthly total solar and wind power is derived using the Map Algebra tool in ArcGIS (Figure 4).

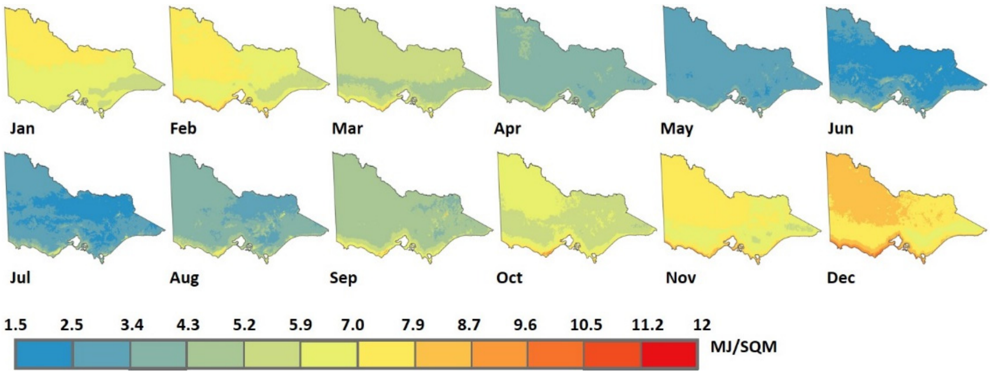

Fig. 4: Total daily wind and solar energy in Victoria, based on multiple years solar and wind energy data

The following two results are evident from the aggregation analysis.

- **Seasonal polarisation of total solar and wind power**. The energy potential for both solar and wind are higher in hot seasons and lower in cold seasons. The aggregation exacerbates the seasonal renewable energy variations. This requires planning strategies that can precisely handle the risks of polarisation in energy production.
- **Alleviation of uneven spatial distribution of wind and solar energy**. Thanks to contrary spatial patterns of solar and wind energy potential in Victoria (i. e. solar power capacity decreases from inland to the coastal areas, while the wind power capacity increases from inland to coastal areas), the aggregation serves to alleviate the uneven spatial distribution of wind and solar energy in Victoria.

3.4 Mapping Total Energy Consumption

Spatial modelling of energy consumption in Australia is conducted using population distribution and per capita energy consumption. The total energy consumption in Victoria is 1,416.9 PJ in 2016 (DEPARTMENT OF ENVIRONMENT AND ENERGY 2018). Total population in Victoria is 5,926,624 (ABS 2017). Per capita energy consumption is calculated as 655 MJ per day. The spatial heterogeneity of total energy consumption in Victoria is calculated using ArcGIS (Figure 5). The mapping result indicates that energy consumption in Victoria is highly concentrated in the metropolitan Melbourne region, while little energy is consumed in most of the eastern and north-western areas in Victoria. This spatial pattern must be understood with the national grid infrastructure and available renewable energy resources to inform energy planning for Victoria.

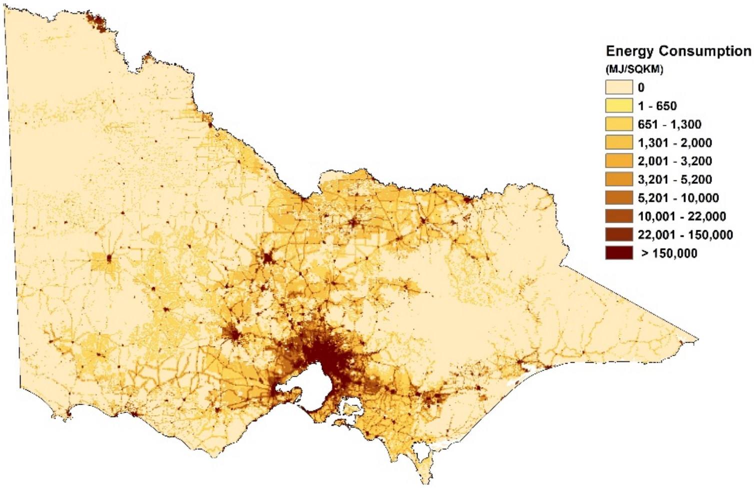

Fig. 5: Spatial heterogeneity of total annual energy consumption in Victoria

4 Discussion

Total annual solar + wind energy availability and planning are discussed in the light of total annual energy consumption, national grid infrastructure, and existing power stations.

4.1 Total Renewable Energy (Solar + Wind)

Total annual wind and solar energy is calculated using daily solar and wind energy (Figure 6). Existing transmission line, power plants and stations data are collected for further analysis of energy landscape planning in Victoria.

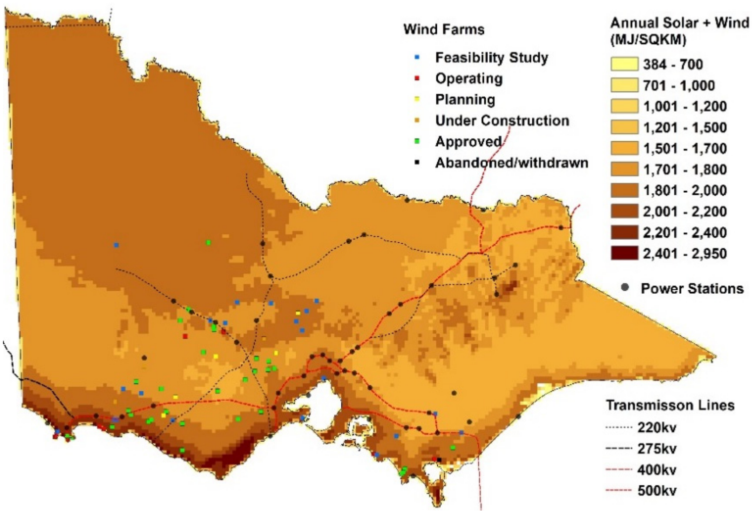

Fig. 6: Spatial heterogeneity of annual renewable energy (solar + wind) and energy infrastructure in Victoria

It is worth noting that most of existing or planned power plants and stations are located in the transect with middle latitude in Victoria, while there are very few within the vast landscape in Northern/North-western Victoria and the coastal zone, despite their higher collective energy potential (Figure 6). So are the transmission powerlines. Therefore, this study provides useful background and evidence for future energy planning in Victoria in terms of effectively engaging the renewable energy landscape for better energy production and consumption outcomes in Victoria.

4.2 Surplus/Deficit between Potential Renewable Energy Production and Total Energy Consumption

Based on total solar and wind energy production and total energy consumption in Victoria, the balance (surplus or deficit) between the two is calculated (Figure 7). It is interesting to note that the populated places (which are within the areas of energy deficit) are chained up by transmission infrastructure, while most of the surplus areas are either not inhabited or with low population density (except some of the coastal towns). Therefore, future renewable energy development needs to be supported by infrastructure especially powerlines construction, given the spatial mismatch between renewable energy availability and energy consumption hotspots. Therefore, it is important to recognise that the development of large-scale infrastructure will have tremendous impacts on the landscape, considering the conflicts between decentralized renewable electricity production and landscape services.

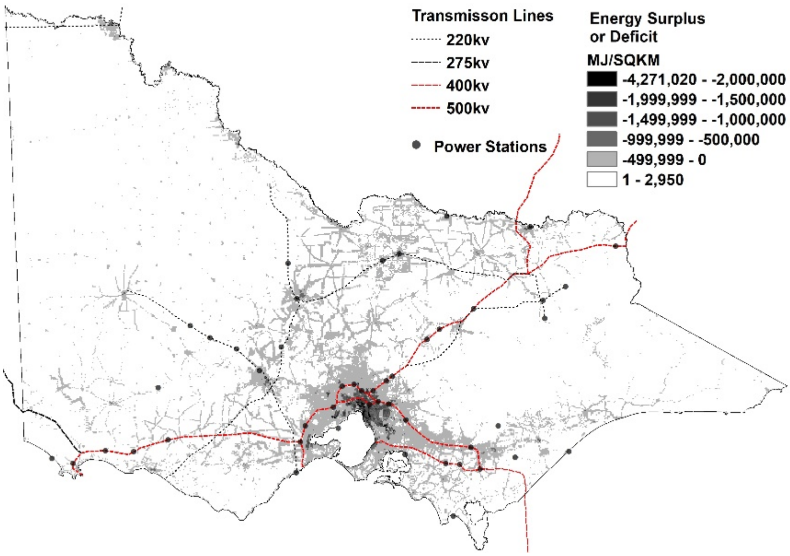

Fig. 7: Surplus/Deficit between Potential Renewable Energy Production and Total Energy Consumption in Victoria

4.3 Limitations of the Study

The results from this study must be understood along with the following limitations. First, as previously mentioned, the datasets used in this study are from various sources at different spatial and temporal scales. Normalisation of the datasets may introduce errors thus undermine the credibility of the findings. Secondly, other renewable energy sources, such as biomass, hydro and geothermal energy are not considered in this study. A comprehensive analysis considering all renewable energy resources will be useful to shed further lights on this topic. Thirdly, very conservative energy capacity factors are used in this study. With the technological advancement and better planning and design of wind/solar farms, the energy capacity factor can be increased, so is the total renewable energy productivity. It is anticipated that renewable energy sources will account for higher proportion in the energy mix in Victoria given all these improvements in the future.

5 Conclusion and Outlook

In this study, GIS-based spatial analysis is used as a tool to investigate solar and wind potential in Victoria's future energy planning through a preliminary strategic outlook of using solar and wind power to contribute to increasing renewable energy generation towards potentially replacing fossil fuel at utility and household levels. As proved in many projects, renewable energy power generation systems can operate under very low or near-zero emissions. Studies like this research are essential to promote renewable energy development and implementation through involving not only identifying areas for developing renewable energy power generation systems or powerlines, but also including the potential for landscape impact and assessment. This study demonstrates that spatial analysis can be integrated into renewable energy planning and decision-making. Future studies must also consider public perception of solar parks and wind farms in the landscape.

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