Finding Synergies between Energy Transition and National Security: On the Complementarity between the Energy Demand of Taiwan and the Variable Renewable Energy Resources of Its Potential Strategic Allies in a Future Dominated by Renewable Energy

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Abstract

We modeled the correlation between the residual load profile of Taiwan and the capacity factor profiles of variable renewable energy power plants at locations within potential strategic allies of Taiwan by 2050. We found that capacity factor profiles of photovoltaic power plants in the US, Australia, Southern Europe, and some parts of Southeast Asia showed positive correlations with the residual load profile in Taiwan, implying good complementarity between the energy demand in Taiwan and the photovoltaic power plants there. Meanwhile, capacity factor profiles of wind power plants from all of the investigated locations did not show the same level of complementarity. These results can serve as a preliminary guideline for Taiwan when finding renewable energy trade partners in the future.

Keywords: *variable renewable energy, green hydrogen, renewable energy trade, national security*

1. Introduction

Since variable renewable energy (VRE) resources such as wind and photovoltaic (PV) power plants require no fuel when generating electricity, it is commonly acknowledged that the development of VRE can increase energy self-sufficiency of a nation, thereby increasing its national security [1]. However, operating the energy system predominantly with renewable energy resources within a nation might require high system costs in order to meet the flexibility requirements resulting from the mismatch of VRE power output profiles and energy demand profiles, especially in the monthly or seasonal timescales [2].

Literature has suggested that interconnections and coordination between nations can reduce the overall system costs of these flexibility requirements [3]. While physical grid connections with other nations might be implausible for Taiwan, international renewable energy trade such as green hydrogen imports might still be a viable solution. In addition, many potential strategic allies of Taiwan due to national security concerns happen to have access to abundant VRE resource potential [4], and a long term coordinated renewable energy trade strategy with those nations might further strengthen the relationship between Taiwan and its allies, thereby enhancing national security of Taiwan. It is thus interesting to investigate whether the VRE resources of these potential allies are good complements to the energy demand in Taiwan.

2. Literature Review

Before we proceed with our study, there are 2 main questions we need to answer: first, is international renewable energy trade really feasible in a future dominated by renewable energy? Secondly, which nations are the potential strategic allies of Taiwan?

For the first question, there are already studies suggesting that by using green hydrogen or other synthesized gas based on green hydrogen as intermediate energy carriers, international renewable energy trade can be economically viable for some nations, even with long distance transportation [5][6]. Exporting green hydrogen to the international market may also lower the overall system cost of the energy system of a nation [7]. Green hydrogen and other synthesized gas are therefore usually regarded as a promising option for international renewable energy trade other than direct cross-border electricity transmission, although the scale of the trade may be more limited than that of the current fossil fuel trade [8].

For the second question, we consider a nation a potential strategic ally of Taiwan either it shares mutual interest in the peace and prosperity in the Indo-Pacific region through a deepened bilateral relationship with Taiwan, or it shares common values on democracy and human rights with Taiwan. For example, the New Southbound Policy, aiming primarily at India and Southeast Asia, is mainly driven by the former factor [9], while the recent strengthening of Taiwan-EU relations can be attributed to the latter [10]. Of course, for some nations such as Japan, South Korea, Australia, New Zealand, and the US, both factors will play equally important roles in shaping the potential alliance with

Taiwan [11].

3. Methodology

3.1 Model Description and Theoretical Backgrounds

To investigate the complementarity between the energy demand of Taiwan and the VRE resources of its potential strategic allies in a future dominated by renewable energy, we modeled the correlation between the residual load (RL) profile of Taiwan and VRE capacity factor (CF) profiles of the chosen locations.

The rationale behind this method is the following: suppose a VRE power plant on the chosen site has a CF profile, $cf(t)$, throughout the year. Suppose the VRE power plant can choose between participating in the regional energy-only market or it can choose to allocate all of its generated electricity to export. If the market clearing price of the region where the VRE power plant is located has the profile $mcp_r(t)$, then the average market value of the power plant in that market will be:

$$\mathrm{MV}_r = \frac{\mathrm{E}[mcp_r(t)cf(t)]}{\mathrm{E}[cf(t)]} \qquad (1)$$

Where $\mathrm{E}[\cdot]$ is the expected value operator over the timeframe we are interested in. Meanwhile, suppose Taiwan also has an energy-only market with a market clearing price profile $mcp_{twn}(t)$, then for the power plant the average market value of exporting to Taiwan will be:

$$\mathrm{MV}_{twn} = \frac{\mathrm{E}[\eta(t)mcp_{twn}(t)cf(t)]}{\mathrm{E}[cf(t)]} \qquad (2)$$

Where $\eta(t)$ is the overall energy efficiency of the intermediate energy carriers before the final energy demand is fulfilled. For example, if the electricity generation of the VRE power plant is transformed to green hydrogen first and then used as fuel for electricity generation, the round trip efficiency will be around 35% [12]; on the other hand, if the green hydrogen exported is to fulfill the green hydrogen end use demand in Taiwan, the efficiency will be assumed to be 100% since transformation from renewable electricity to green hydrogen will have to be conducted anyway even if the same green hydrogen demand is met by renewable electricity in Taiwan.

Without considering other factors such as transportation costs, storage costs, or portfolio optimization strategies in different regional markets at different time periods, renewable energy export of a VRE power plant to Taiwan will make economic sense only when $\mathrm{MV}_{twn} \geq \mathrm{MV}_r$. From equations (1) and (2) we can see that the higher correlation between the market clearing price profile of a regional market and the CF profile of a VRE power plant, the greater market value the VRE power plant will have in that regional market. It is also obvious, both from empirical analysis [13] and theoretical derivations [14], that the market clearing price profile in a regional market is highly correlated to the RL profile of that region. Therefore, the correlation between the RL profile of Taiwan and the CF profile of a VRE power plant can serve as a preliminary criterion for assessing the viability of renewable energy export from a VRE power plant to Taiwan.

3.2 Estimation of the RL Profile of Taiwan

We assumed that by 2050, nearly all of the energy demand in Taiwan would be electrified. Thus the components of RL in Taiwan by 2050 were modeled as:

$$\mathrm{D(t)} = \alpha_i \mathrm{I(t)} + \alpha_c \mathrm{C(t)} + \alpha_h \mathrm{H(t)} + \alpha_v \mathrm{V(t)} \qquad (3a)$$

$$\mathrm{VRE(t)} = \mathrm{Cap}_w^{twn} \cdot cf_w^{twn}(t) + \mathrm{Cap}_{pv}^{twn} \cdot cf_{pv}^{twn}(t) \qquad (3b)$$

$$\mathrm{RL(t)} = \mathrm{D(t)} - \mathrm{VRE(t)} \qquad (3c)$$

Where $\mathrm{D(t)}$ is the equivalent electricity demand profile; α_i, α_c, α_h, α_v, the expected annual equivalent electricity demand for the industrial, commercial, household, and transportation sectors; $\mathrm{I(t)}$, $\mathrm{C(t)}$, $\mathrm{H(t)}$, and $\mathrm{V(t)}$ the non-dimensionalized equivalent electricity demand profiles for the industrial, commercial, household, and transportation sectors; $\mathrm{VRE(t)}$ the VRE power output profile; Cap_w^{twn} and Cap_{pv}^{twn} the wind and PV capacity; $cf_w^{twn}(t)$ and $cf_{pv}^{twn}(t)$ the CF profile of wind and PV power plants; $\mathrm{RL(t)}$ the RL profile.

The non-dimensionalized equivalent electricity demand profiles by 2050 resulted from the original final energy data between 2010 to 2019 from the statistics of the bureau of energy [15], and they captured the seasonal variations of energy demand across different sectors. To calculate the equivalent electricity demand of non-electricity demand in the original data, some assumptions had to be made. For example, we assumed fossil fuel consumption in the industrial sector could only be replaced with green hydrogen, while in the commercial and household sectors it could be replaced with direct electrification. This meant that for the same heat value of fossil fuel final demand, the industrial sector would have a higher equivalent electricity demand due to power-to-gas efficiency losses (which we assumed to be 70% [16]). On the other hand, electric vehicles were assumed to be 3 times more efficient than internal combustion engines in terms of transforming final energy demand into actual vehicle movement [17] when obtaining the equivalent electricity demand of the transportation sector.

For the industrial, the commercial, and the transportation sectors, long term trends were not significant in the data, so the non-dimensionalized profiles of these energy demand were computed by dividing the equivalent electricity demand by the average annual value throughout the decade. Meanwhile, for the household sector we observed an obvious difference of the long term trend for each month. After conducting linear regression analysis for the equivalent electricity demand of each month as a function of years, we found that only the trends of the months between May to September showed statistical significance (table 1). Thus we extrapolated the trends in these months into the future, while assuming the mean of the equivalent electricity demand would remain the same for other months. By adding the extrapolated trend of the equivalent electricity demand by 2050 and the noise signal (the residuals after the trend in each month was subtracted) in the real data for different months, the non-dimensionalized profiles of the equivalent electricity demand for the household sector could be constructed (fig. 1).

The expected annual equivalent electricity demand by 2050 for different sectors was derived mainly from the proposed values in the "L1 scenario" of [18]. Accordingly, the default annual equivalent electricity demand by 2050 was set to be 32.2% higher than the average value between 2010 to 2019 for the industry sector, 26.7% higher for the commercial sector, and 8.71% lower for the transportation sector. We however considered the L1 scenario of [18] for household sector energy demand reduction too optimistic and instead modeled the reduction proportional to the expected population decrease (from 23 million in the 2010s to 20 million by 2050), after the growth of the demand due to the long term trend shown in (table 1) was extrapolated into 2050. This resulted in a slight 1.64% decrease of the annual equivalent electricity demand by 2050 for the household sector, compared with the average value between 2010 to 2019.

The VRE CF profiles in Taiwan were derived from dividing the actual VRE electricity generation by the installed VRE capacity between 2010 to 2019 from the statistics of the bureau of energy [15].

Since there have not yet been official goals of VRE capacity expansions by 2050 in Taiwan, assumptions had to also be made. The PV capacity modeled or estimated by 2050 in recent studies varied between 125 GW [19] and 325 GW [20], while the figure for wind capacity has been between 50 GW [21] and 70 GW [20]. In this paper we used 180 GW of PV capacity and 60 GW of wind capacity as the default value by 2050 for our model.

The resulting RL profile can be found in (fig. 2). Note that since the original data has a time length of 10 years, the modeled RL profile also has a time length of 10 years; we should interpret the profile as a consecutive 10-year-long time series assuming the statistical parameters of the profiles remain the same as what we have estimated for Taiwan by 2050.

3.3 Data for VRE CF Profiles of Other Regions

The locations where VRE CF profiles were chosen for investigation was filtered under the following criteria:

1. The location must be within a nation that had been identified as a potential strategic ally of Taiwan in section 2.
2. The VRE resource abundance of the location must be sufficient; preferably the highest among the nation it was located. A rule-of-thumb threshold was used: for wind power plant potential, the average annual CF must be greater than 35%, and for PV power plant potential, the average annual CF must be greater than 16%. Ireland was the only exception for this set of rules (see table 2).
3. The nation where the location was situated must be identified as a "renewable-rich" nation without water constraints in [4].

In the end we chose 7 locations for the analysis of export from wind power plants and 9 locations for the analysis of export from PV power plants (table 2). Their monthly CF data between 2010 to 2019 (extracted from Renewables.ninja [22]) were used.

4. Results and Discussion

Our results are shown in table 3. Wind power plants of all the locations chosen had CF profiles that were negatively correlated with the RL profile in Taiwan, while CF profiles of PV in the US, Australia, and Southern Europe showed positive correlations with the RL profile in Taiwan. CF profiles of PV in Southeast Asia showed mixed results: while in Thailand and Vietnam they were negatively correlated with the RL profile in Taiwan, in Indonesia it was positively correlated.

The negative correlations of CF profiles of VRE power plants in Australia and PV in some parts of Southeast Asia with the RL profile in Taiwan are interesting because these nations are the nearest to Taiwan in the chosen locations. Negative correlations of the CF profiles of the VRE power plants with the RL profile in Taiwan implies potentially higher investment costs in either overbuilding of VRE power plants or energy storage to meet the same amount of renewable energy export to Taiwan. On the other hand, PV power plants in the US and Europe, while having CF profiles highly correlated with the RL profile in Taiwan, will require longer distances of transportation for renewable energy export to Taiwan. The magnitudes of these costs will determine the price spread needed between the market clearing prices in Taiwan and these regions and therefore the overall cost effectiveness of renewable energy export from these regions to Taiwan. And of course, for wind power plants in Europe, whose CF profiles showed negative correlations with the RL profile of Taiwan and will also require longer distances of transportation for renewable energy export to Taiwan, it will need the highest price spread between market clearing prices to make renewable energy trade viable.

The sensitivity of the results to variations of different parameters in the RL profile of Taiwan are also shown in table 3. In general, the correlation coefficients were most sensitive to the variation of Cap_{pv}^{twn}, an increase of Cap_{pv}^{twn} tended to decrease the absolute magnitude of the correlation coefficients, and an increase of Cap_{w}^{twn} or $\mathrm{D(t)}$ tended to increase the absolute magnitude of the correlation coefficients, although some exceptions to these rules occurred (for example, the increase of $\mathrm{D(t)}$ decreased the absolute magnitude of the correlation coefficient between the CF profiles of both wind and PV power plants in Australia and the RL profile in Taiwan, and vice versa).

5. Conclusions

This paper serves as a preliminary study to enable further investigation on the topic. We found that, apart from their abundant renewable energy resources, the CF profiles of PV power plants in some of the potential strategic allies of Taiwan were positively correlated to the RL profile of Taiwan, implying good complementarity between the energy demand in Taiwan and the PV resources there. The nations where these locations are situated might therefore be the priority to investigate further when Taiwan seeks renewable energy trade partners in the future. CF profiles of wind power plants from all of the chosen locations, in the meantime, did not show the same level of complementarity. Of course, this does not rule out the possibility of renewable energy trade from these power plants, but it might need a much higher price spread between the market clearing prices of Taiwan and those areas to make such trade viable compared with the PV power plants that showed a better complementarity.

Improvements can be made in the model. The CF profile for wind power plants in Taiwan was obtained from a time period when onshore wind power plants dominated Taiwan's wind power plant fleet, but in the future it will be offshore wind power plants that will be the main pillar in the fleet. With higher CF especially in winter months, the seasonal imbalance of RL profile of Taiwan by 2050 might increase, thereby increases the viability of renewable energy export from VRE power plants which generate more electricity in the summer months of Taiwan (e.g. PV power plants in Texas, California, Tenggara, Portugal, and Spain). On the other hand, CF profiles from PV power plants in the future depends on the efficiency growth of PV modules and the average DC/AC ratio of the power plants. A higher average DC/AC ratio of the PV power plants will lead to a less variable CF profile which should theoretically have a similar impact on the seasonal imbalance of RL profile as using more offshore wind power plants.

Furthermore, in this paper we did not consider the potential structure changes of the energy demand in detail. For example, one can imagine that in a world where coal is completely phased out and green hydrogen is used for steel production, the steel industry will be more competitive in locations where abundant green hydrogen is available. So the steel industry in Taiwan might shrink significantly in the future, changing the energy demand profile of the industrial sector considerably.

In the future, building upon the methodology and the results of this paper, we can model the RL profile of the chosen locations and even the market clearing prices of those locations and Taiwan to determine the viability of renewable energy trade between them in a more robust manner. In addition, although some nations might not be considered "renewable-rich", the seasonal variability of VRE power plants still means that they might have excess renewable energy in some times of year. PV power plants in Germany, for example, might be able to export large amounts of surplus energy in summer months, and the viability of renewable energy export from these power plants to Taiwan in summer can also be investigated in the future.

Ultimately, after diplomatic relations, overall costs, and risk exposure of trading routes considered, we can categorize different levels of viability of renewable energy trade from every nation to Taiwan and thereby determine an optimal long term renewable energy trade strategy for Taiwan.

6. References

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7. Figures and Tables

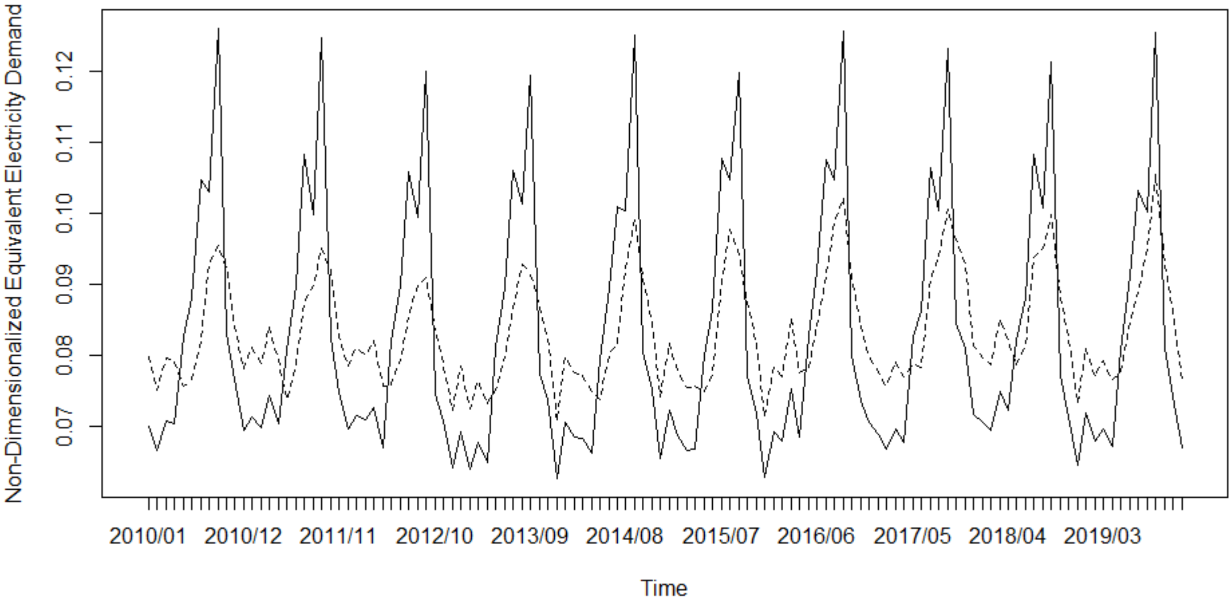

Fig. 1. Non-dimensionalized equivalent electricity demand profiles for the household sector in Taiwan. The dashed line is the actual profile, while the real line indicates the modeled profile by 2050.

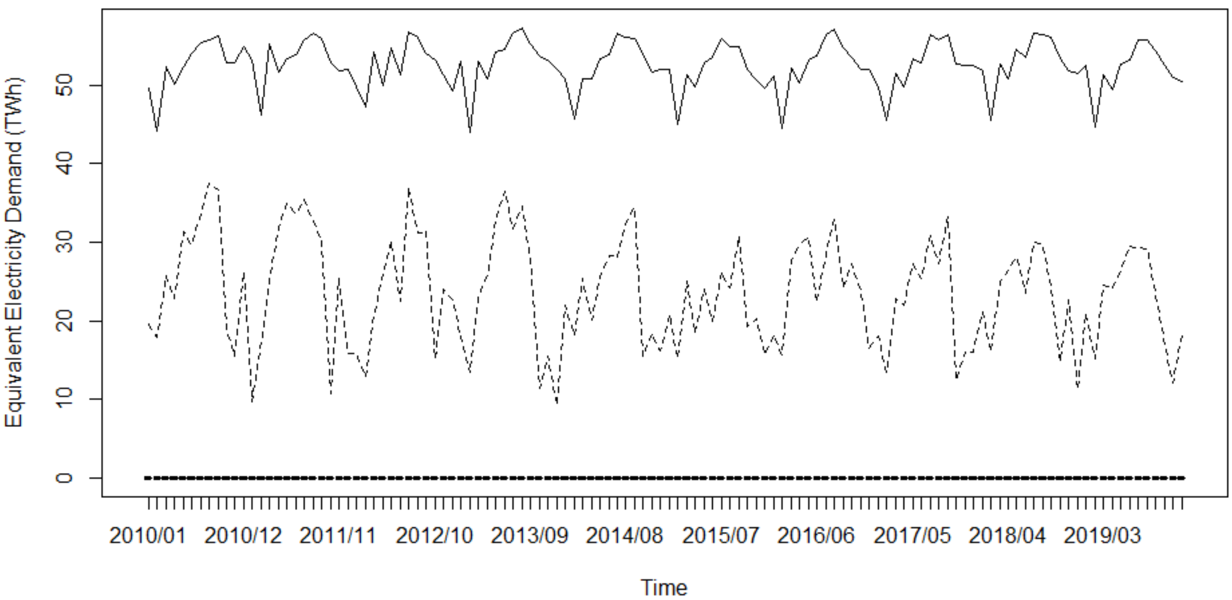

Fig. 2. Equivalent electricity demand and residual load profiles in Taiwan by 2050. The real line is the equivalent electricity demand profile, while the dashed line is the residual load profile.

Table 1. Statistical significance of the trends of equivalent electricity demand for the household sector. The t-statistic was obtained by dividing the estimated slope of the trend by the estimated standard error of the slope. Months that have a significant value of t-statistic (greater or equal to 2) are highlighted in red.

Month	Est. Slope of the Trend (MWh / yr)	Est. Standard Error of the Slope (MWh / yr)	Value of t-statistic
January	-6416.239	9657.333	-0.6643904
February	3035.309	15859.497	0.1913875
March	5360.973	25871.904	0.2072121
April	6910.333	18262.569	0.3783878
May	30058.105	9699.511	3.0989301
June	39156.248	15063.413	2.5994275
July	60514.274	19817.913	3.0535140
August	39677.924	16247.276	2.4421277
September	78983.138	22074.306	3.5780576
October	21105.740	25657.316	0.8226012
November	37006.746	24126.411	1.5338687
December	6034.194	27422.396	0.2200462

Table 2. Chosen locations for the analysis of export from wind and PV power plants. For the capacity factor of wind, we assumed G128 5000 with a hub height of 100 meters were installed at the investigated locations. For the capacity factor of PV, we assumed that the PV panels were facing south for locations in the northern hemisphere and north for locations in the southern hemisphere; the tilt angle of the PV panels was assumed to be 5 degrees less than the magnitude latitude if the magnitude of latitude was greater than 5 degrees and 0 degree if it was less than or equal to 5 degrees.

Wind				Photovoltaic			
Location	**Latitude (deg)**	**Longitude (deg)**	**Annual Average CF**	**Location**	**Latitude (deg)**	**Longitude (deg)**	**Annual Average CF**
Texas	31.8160	-99.5121	39.35%	**Texas**	31.8160	-99.5121	19.63%
Iowa	41.9217	-93.3123	39.64%	**California**	36.7015	-118.7560	22.35%
South Australia	-30.5344	135.6301	36.35%	**Northern Territory**	-19.8516	133.2303	21.16%
Western Australia	-25.2303	121.0187	36.69%	**Western Australia**	-25.2303	121.0187	21.38%
Denmark	55.6702	10.3333	36.33%	**Thailand**	14.8972	100.8327	16.34%
Ireland	52.8652	-7.9795	34.61%	**Tenggara**	-8.5657	120.6979	18.12%
Nordland	67.2756	13.8624	39.67%	**Vietnam**	13.2904	108.4265	16.78%
				Portugal	40.0333	-7.8896	17.16%
				Spain	39.3261	-4.8380	20.06%

Table 3. Correlation coefficients between the RL profile in Taiwan and the VRE CF profiles at the chosen locations. The sensitivity of the results to variations of total demand and installed capacity of VRE power plants in Taiwan is also shown in the table; in each row, the upper values correspond to the sensitivity when a variable is increased by 10%, and the lower values correspond to the sensitivity when a variable is decreased by 10%. CA = California, SA = South Australia, NT = Northern Territory, and WA = Western Australia.

Wind					Photovoltaic				
Location	**Default**	**±10% D(t)**	**±10% Cap_w^{twn}**	**±10% Cap_{pv}^{twn}**	**Location**	**Default**	**±10% D(t)**	**±10% Cap_w^{twn}**	**±10% Cap_{pv}^{twn}**
Texas	-0.267	-0.282 -0.251	-0.271 -0.262	-0.247 -0.286	**Texas**	0.498	0.495 0.501	0.510 0.482	0.486 0.508
Iowa	-0.456	-0.466 -0.444	-0.461 -0.448	-0.437 -0.473	**CA**	0.584	0.585 0.583	0.602 0.561	0.562 0.604
SA	-0.166	-0.156 -0.178	-0.177 -0.153	-0.165 -0.167	**NT**	-0.291	-0.286 -0.296	-0.291 -0.290	-0.295 -0.286
WA	-0.061	-0.055 -0.066	-0.070 -0.050	-0.056 -0.065	**WA**	-0.429	-0.423 -0.435	-0.442 -0.413	-0.420 -0.437
Denmark	-0.604	-0.606 -0.601	-0.617 -0.586	-0.584 -0.621	**Thailand**	-0.603	-0.616 -0.589	-0.608 -0.595	-0.582 -0.622
Ireland	-0.454	-0.459 -0.448	-0.465 -0.440	-0.435 -0.471	**Tenggara**	0.217	0.228 0.205	0.234 0.196	0.186 0.246
Nordland	-0.627	-0.632 -0.622	-0.642 -0.609	-0.605 -0.648	**Vietnam**	-0.416	-0.435 -0.396	-0.415 -0.416	-0.397 -0.434
					Portugal	0.649	0.654 0.643	0.666 0.627	0.623 0.673
					Spain	0.626	0.630 0.621	0.645 0.602	0.599 0.651