Meta-analysis of Energy Innovation System of 39 Countries

Very preliminary draft paper – comment welcome; please do not cite

Fionn Rogan[1,2]
Paul Bolger[2]
Brian Ó Gallachóir[1,2]

[1] *School of Engineering, University College Cork, Ireland*
[2] *MaREI centre, Environmental Research Institute, University College Cork, Ireland*

Abstract

The challenges for all countries of the energy transition to a decarbonized energy system necessitates a systematic approach. The energy innovation system framework has been used to analyse and describe the challenges of energy technology development, deployment and diffusion and innovation system indicators have been used to evaluate progress on a country-by-country basis. This paper develops a broader set of energy innovation system indicators than previously to track the performance and type of energy innovation system in 39 countries representing 84% of energy-related GHG emissions. The analysis (1) finds a relationship between how innovative and competitive countries are and how advanced their energy and environmental performance is, (2) describes 7 country categories based on the distribution of scores in economic and environmental indices, and (3) analyses and describes some of characteristics, success factors and lessons for countries managing the energy transition to a decarbonised energy system.

Keyword set

energy technology innovation system; innovation system indicators; energy transition

Introduction:

The global energy system contributes approximately 76% of global GHG emissions which are the main driver of anthropogenic climate change (IPCC 2014). To limit the global temperature increase to "well below 2 degrees" (as defined in the Paris Accords), a radical decarbonisation of the worlds energy system is required to happen over the period to 2050. While the goal of this energy transition is relatively easy to define (net carbon neutrality by 2050), the challenges and difficulties in achieving this goal are without precedent in human history.

Many different analytical frameworks have been used to define the problem and there is broad consensus that innovation in technology development and deployment and innovation in energy system organisation are both required. The complexity of the global energy system and the variability of energy systems in different countries mean there is no equivalent to a recipe or guide on how to decarbonize energy system. For every country, the energy transition will be different.

The field of innovation systems has been used in many different technological fields (e.g. ICT, biotechnology, pharmaceutical, agri-food, etc) to give insights to the many varied challenges of managing, governing and leading technological change. Innovation systems can bring insight to the challenges inherent in the energy transition, but in doing so, the particular characteristics of the energy system must be borne in mind; these include (but are not limited to) the following: changes in the energy system take a long time and are bound by inertia; it is capital intensive; owing to the level of regulation involved it has a hybrid public/private character; it has system characteristics and is bound by infrastructure (Gallagher et al. 2012; Mads Borup 2013).

In order to bring insights to the status of the energy technology innovation system in a particular country, indicators to measure the performance and type of innovation system are essential. Many metrics have been proposed and a common challenge is data availability for particular countries and data harmonization of indicators for comparisons between countries.

This paper assembles a new data set of energy innovation system metrics from a range of different sources including direct indicators (e.g. energy RD&D spend, patents) from organisations such as OECD & IEA, together with economic indices from a number of separate published sources not directly focused on the energy system. This combination of direct and indirect sources enables a meta-analysis of the energy innovation systems of 39 countries (representing 83% of global energy consumption and 84% of global energy-related emissions) that is broader than many other analyses of the energy innovation system that focus on simple measured inputs and outputs. The combination of metrics, both micro & macro, is applied to a range of different countries to gain insights into the challenges and successes of the energy system transition that is, or isn't, taking place.

The paper is organised as follows: section 2 describes the methodology which includes the data used, the countries examined, the research questions asked, and the methodology for answering them; section 3 summarizes the results; sections 4 concludes.

Methodology

Data

The data used are a set of six independent indices that measure the world's countries for their performance on innovation, competitiveness and entrepreneurship metrics, and environmental performance, energy sustainability, and cleantech innovation. The indices are all from either 2014 or 2015 and come from a variety of global consultancies and firms, which either develop their own datasets or assemble them from existing country or IGO datasets. The six indices are can be broadly divided into either economic indicators or environmental indicators and are shown in Table 1.

Table 1 – Economic and environmental indicators in the analysis

Economic Indicators	**Environmental Indicators**
Global Innovation Index (2014)	Environmental Performance Index (2014)
Global Competitiveness Index (2014)	Energy Sustainability Index (2014)
Global Entrepreneurship Index (2015)	Cleantech Innovation Index (2014)

In addition, the following data sources were also used:

- OECD data on innovation system metrics
- IEA data on Energy R&D spend & patents

Countries

Countries were chosen based on making the most of data availability but also broadening and maximising the diversity of countries, i.e. it would have been possible to make the analysis more comprehensive for a smaller number of countries (for whom data availability is excellent) or make the analysis more far reaching but shallower. These countries represent a majority of world's energy consumption (83%) of global energy consumption and global energy-related emissions (84%) (source: BP Statistical yearbook 2015). A full list is shown in Table 2.

Table 2 – List of countries in analysis

EU		**OECD**	**Non-OECD**
Austria	Ireland	Australia	Argentina
Belgium	Italy	Canada	Brazil
Bulgaria	Netherlands	Israel	China
Czech Republic	Poland	Japan	India
Denmark	Portugal	Korea	Indonesia
Finland	Romania	Mexico	Russia
France	Slovenia	Norway	Saudi Arabia
Germany	Spain	Switzerland	Singapore
Greece	Sweden	Turkey	South Africa
Hungary	UK	USA	

Research questions

The following are the two basic research questions in this analysis:

1. Are countries that are ranked the highest for innovation, competiveness, and entrepreneurship (i.e. economic) metrics also ranked the highest on metrics for environmental performance, energy sustainability and clean-tech (i.e. environmental) performance?
2. For individual scores, what is the relationship between innovation, competiveness, and entrepreneurship (i.e. economic) metrics and environmental performance, energy sustainability and cleantech (i.e. environmental) performance?

Methodology

The first research question is addressed by basic correlation metrics (R^2, correlation matrix, and visual examination). One of the outcomes of the first research question was to divide the 39 countries in the analysis into 7 categories based on their ranking and distribution of performance in the overall results. These 7 categories are listed and explained in the results section.

The second research question was answered by (for each of the 7 country categories) examining the relationships between individual scoring on the economic indicators and the environmental indicators. It is not a formal modelled analysis. The purpose of the analysis was to gain insights into success factors for countries managing their energy transition.

Results

The results are described for each research question.

Research question 1

Are countries that are ranked the highest for innovation, competiveness, and entrepreneurship (i.e. economic) metrics also ranked the highest on metrics for environmental performance, energy sustainability and clean-tech (i.e. environmental) performance?

At the macro-level of the economic categories and environmental categories, there is strong correlation between the performance of countries (R^2 = 0.81), i.e. countries that are ranked in the top percentile for economic performance tend to be in the top percentile for environmental performance, and vice-versa. At the higher performing end of the scale, the economic and environmental ranking of countries tends to be close together; at the lower end of the scale, there is increasing variance between the economic and environmental ranking of countries, see Figure 1.

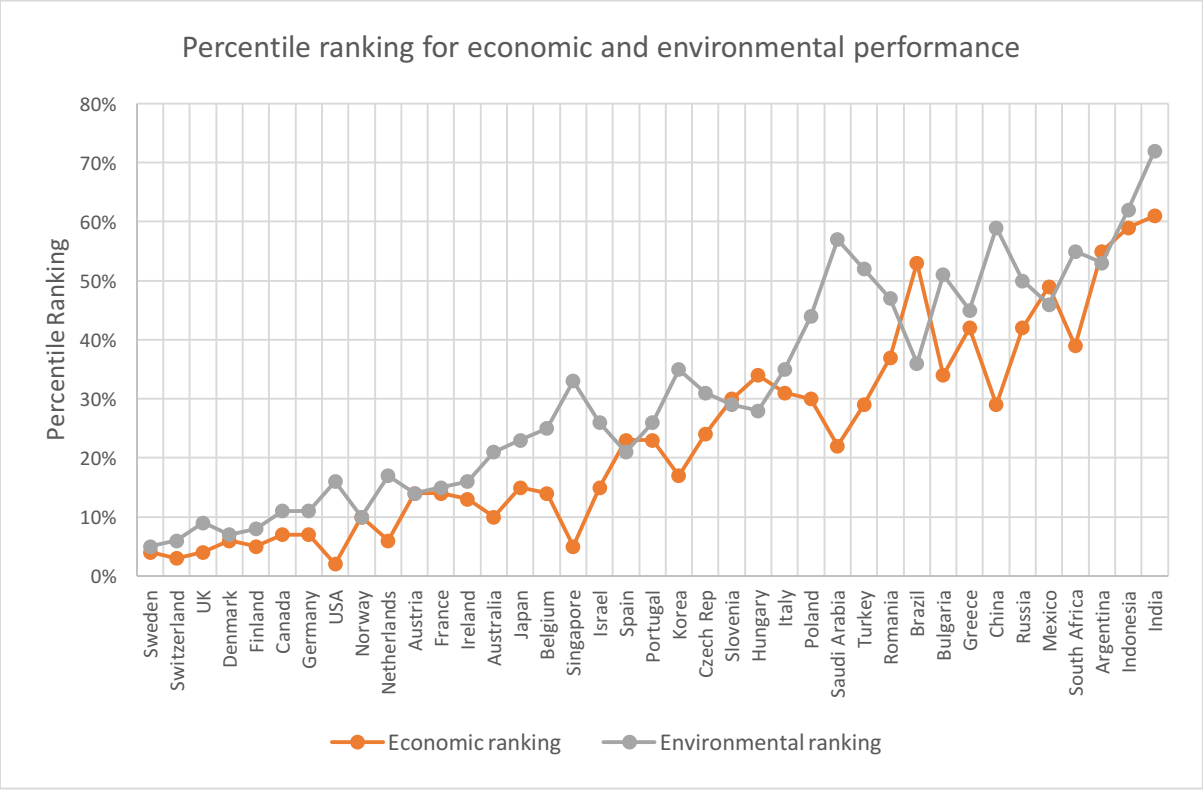

Figure 1

When drilling into the data, i.e. looking at how individual indices correlate, and how top performing countries correlate compared to middle and lower ranking countries, the correlations become much weaker. There is much variability for the indices and the countries. It is difficult to discern clear patterns of correlation. This discussion below mostly describes weak trends.

For results for correlation of indices is shown in Table 11. In these results there is most correlation within the category of economic and within the category of environmental. Across these categories, the entrepreneurship index has the highest correlation with an environmental indicator whereas the competitiveness indicator is the most poorly correlated with the environmental indicators. The environmental performance indicator is the best correlated with economic indicators.

Based on the results of the country performance, 7 country categories were developed, as shown in Table 3.

Table 3 – Country categories

	Category	**Description**
1	TOP (consistent)	Consistently high scoring or top ranking on all or nearly all metrics
2	TOP (exceptions)	Consistently high scoring or top ranking with notable exception of one or two moderate scores
3	MODERATE (exceptions-high)	Moderate rankers with exception of one or two top score
4	MODERATE (consistent)	Moderate rankers with consistent moderate scoring on all nearly metrics
5	MODERATE (exceptions-low)	Moderate rankers with notable exception of one or two very low score
6	CATEGORY DIFFERENCE	Very high economic score with very low environmental score
7	LOW	Consistently lowest scorers and rankers on nearly all metrics

The following countries are sorted into the following categories, see Table 4.

Table 4 – Countries in each category

TOP_CON	TOP_EXCP	MOD_EXCP-HIGH	MOD_CON	MOD_EXCP-LOW	CAT_DIFF	LOW
Sweden	Canada	Netherlands	Ireland	Slovenia	Singapore	South Africa
Switzerland	Germany	Australia	Belgium	Poland	Saudi Arabia	Argentina
UK	USA	Japan	Portugal	Romania	Turkey	Indonesia
Denmark	Norway	Israel	Korea	Brazil	China	India
Finland	Austria	Spain	Hungary	Bulgaria		
	France	Czech Rep	Italy	Greece		
				Russia		
				Mexico		

Research question 2

For individual scores, what is the relationship between innovation, competiveness, and entrepreneurship (i.e. economic) metrics and environmental performance, energy sustainability and cleantech (i.e. environmental) performance?

TOP (consistent)

Many countries in this category are commonly ranked top of global indices, see Table 5 All of these countries have some type of long-term energy plan, few have large reserves of fossil fuels but many have large hydro resources (which boosts their renewables share). Despite their very high rankings for governance, they are still facing challenges in commercialising cleantech and deploying more renewables. They are likely to be technology leaders and exporters in some area (though not necessarily energy).

Table 5 – Top consistent ranking countries

	Innovation	Competiveness	Entrepreneurship	Environment	Energy	Cleantech
SWE	2%	7%	4%	5%	2%	10%
SWZ	1%	1%	7%	1%	1%	20%
DNK	6%	9%	5%	7%	4%	13%
FI	3%	3%	11%	10%	6%	5%
UK	1%	6%	3%	7%	3%	15%

In this analysis of factors relevant to their energy system, the following commonalities are noted:

- All countries have some type of long-term plan to give direction to their energy transition. The presence of a long-term plan seems to be one of the most important characteristics for a country to have a progressive energy innovation system, although what type of long-term plans are best isn't yet known
- None of the countries have large fossil fuel reserves or have economies dominated by energy export. The country with the largest fossil fuel reserves (the UK) is still a net energy importer.
- All countries have high levels of renewables in their electricity and energy supply mix, though for many countries these are hydro resources
- All countries are technology developers and exporters in some areas
- All countries score very high for environmental factors, with little or no associated negative effects for human health
- All countries rank high for quality and good governance
- In terms of market size,
- All countries score well for entrepreneurship qualities, though commercialisation challenges are noted (especially for cleantech) for most countries
- Within-country collaboration levels (university-industry) are generally high, but international collaboration levels are lower (i.e. not top ranked)
- Government procurement of advanced tech moderate ranking

TOP (exception)

Unlike the TOP_CON category, many countries in the TOP_EXCP have large fossil fuel reserves, see Table 6. This makes them prone to carbon lock-in and more likely to lead to politically conflicting priorities regarding climate change and cleantech. Compared to other countries with fossil fuel reserves, negative environmental & health consequences are minimized (though still evident).

Table 6 – Top exception ranking countries

	Innovation	Competiveness	Entrepreneurship	Environment	Energy	Cleantech
NWY	10%	8%	12%	6%	2%	1%
CA	8%	10%	2%	13%	5%	9%
GER	9%	3%	8%	3%	9%	13%
AU	14%	15%	14%	4%	5%	8%
FR	15%	16%	9%	15%	7%	2%
US	4%	2%	1%	19%	9%	30%

Top rankers (with exception of one moderate score)

- With the exception of Austria, none of the countries in this category have a long term energy transition plan
- Many countries are significant energy exporters (lock-in)
- R&D budgets tend to be slightly more peaky and less likely to be focused on renewables than the top ranking countries
- Environmental scores are high, though some negative side-effects on air quality & health
- Conflicting political priorities evident from very high entrepreneurial rankings, but cleantech rankings not top
- Quality of governance high and market size large

MODERATE (exception of one or two top scores)

The countries in this category are all advanced economies, with mostly medium ranking on indicators, see Table 7 While all of these countries score very well on one or two metrics, the range of metrics show that these top rankings are exceptional. This validates the approach of using a range of metrics and approximates an innovation system approach which covers the range of inputs and outputs. The distribution of scoring varies: for example, Japan & Australia score very differently in terms of entrepreneurship & competiveness; Israel scores very high for cleantech, but very low for energy sustainability, the opposite distribution to all other countries in this category. Netherlands, Spain and Czech Republic all score high for environment but low for cleantech.

Table 7 – Moderate exception ranking countries

	Innovation	Competiveness	Entrepreneurship	Environment	Energy	Cleantech
NL	3%	6%	10%	6%	11%	28%
AS	12%	15%	2%	2%	10%	55%
SP	19%	24%	25%	4%	12%	65%

JA	15%	4%	25%	15%	18%	30%
IS	10%	19%	17%	22%	51%	3%
CZ	18%	26%	27%	3%	22%	75%

The inconsistency of scoring reveals how strengths in one areas can be inhibited by relative weaknesses in another area, for example:

- Low entrepreneurship rankings for Japan severely weaken the impact of the world leading investment in energy R&D: this is a problem not just for Japan, but also the rest of the world given that Japan
- Israel scores very well for cleantech, but has weaknesses in many other areas especially political commitment (and an absence of a long term plan), which inhibit their ability to
- Countries without long term plan: for decade prior to 2011, based on nuclear R&D statistics (66% nuclear R&D spend), Japan had a de-facto long term plan of nuclear, but post-Fukushima this was put on indefinite hold
- Governance is not a challenge in terms of implementation
- World leading in technology development in certain areas (including, but not necessarily energy)

MODERATE (consistent)

Countries in this category are consistent moderate scoring, though without very high and very low scoring, Table 8. They tend not to be technology leaders, but have demonstrated early follower status.

Table 8 - Moderate consistent ranking countries

	Innovation	**Competiveness**	**Entrepreneurship**	**Environment**	**Energy**	**Cleantech**
IRE	8%	17%	13%	11%	17%	14%
BG	16%	13%	12%	20%	16%	23%
POR	22%	25%	23%	10%	19%	15%
HY	24%	42%	35%	16%	26%	17%
IT	22%	34%	38%	12%	22%	40%
KO	11%	18%	22%	24%	43%	43%

- Medium to low category for energy R&D investment (with exception of Korea)
- Not technology exporters or leaders but many successful followers: Portugal, Ireland (wind energy)
- Not energy producing countries (have energy import dependency)
- Environmental scoring main weakness is air quality with associated health impacts
- Governance and institutions are strong, but no long-term policy plans; in the competitiveness indicator policy instability is a high ranking “problematic factors for doing business”
- Korea similar to Japan: very high for patents/share of environmental inventions, but very low for entrepreneurship ranking

MODERATE (exception of one or two low scores)

Many of the countries in this category have large energy reserves and are energy exporters. This is undoubtedly contributing to economic growth and raising their standard of living, but environmental degradation, negative health impacts and carbon lock-in are clear challenges. Levels of cleantech investment are significant lower than top ranking countries with energy reserves, though share of tax revenue from energy tax are significantly higher.

	Innovation	Competiveness	Entrepreneurship	Environment	Energy	Cleantech
SLV	20%	49%	22%	8%	19%	22%
BRZ	43%	40%	77%	43%	23%	16%
POL	31%	30%	29%	17%	33%	35%
GRC	35%	56%	36%	13%	40%	31%
MX	46%	42%	58%	37%	29%	29%
RO	38%	41%	32%	48%	42%	10%
RU	34%	37%	54%	41%	39%	23%
BU	31%	38%	34%	23%	52%	36%

- These countries are much more likely to be energy export (with associated carbon lock-in and "high energy tax take lock-in"); they tend to get more tax revenue from energy than other countries, especially compared to top ranking countries that have energy reserves (e.g. US, Canada, Norway)
- Environmental degradation and air pollution and link to health evident, especially for indoor air quality
- Quality of electricity negatively affecting economy and society; though energy access not generally a problem
- Countries with partial or negligible commitment to cleantech; cleantech R&D budgets very low or zero (indigenous capacity in terms of renewables very low)
- No long-term energy transition plans
- Quality of governance and institutions having a negative impact; entrepreneur institutional scores lower than individual; corruption rated as a barrier to business;
- Transition for countries with and without large fossil fuel reserves will be very different
- Energy transition to decarbonized energy systems for these countries considerably more radical than top ranking countries

CATEGORY DIFFERENCE

This category has been created to capture countries whose environmental, climate change and energy sustainability considerations have been largely relegated in favour of economic priorities, see Table 9. With the exception of Singapore all these countries have very large energy reserves and are also very low investors in cleantech.

Table 9 – Category Difference ranking countries

	Innovation	Competiveness	Entrepreneurship	Environment	Energy	Cleantech
SING	5%	1%	8%	2%	32%	50%
TRK	38%	31%	19%	37%	57%	38%
SARB	27%	17%	24%	20%	53%	74%

CH	20%	19%	47%	66%	57%	67%

- Environmental & climate factors demoted in preference to economic factors
- Consequences for environment, air quality, health (e.g. child mortality) very negative
- Very little or contradictory emphasis on cleantech
- Large energy export countries
- Carbon lock-in and "high energy tax take lock-in"
- Quality of electricity system negatively affecting quality of life

LOW

Countries in this category rank consistently low for both economic and environmental criteria, Table 10. They all have populations with less than 100% access to electricity (varies from 75%-94%). There are negative environmental impacts from too little access to electricity and from the "wrong kind" of energy (e.g. indoor air pollution from biomass burning). Upgrading and maintaining their energy system is hampered by lack of access to financial capital and human capital. Quality of institutions and governance inhibiting countries.

Table 10 – Low ranking countries

	Innovation	**Competiveness**	**Entrepreneurship**	**Environment**	**Energy**	**Cleantech**
ARG	49%	72%	43%	52%	47%	35%
SAFR	37%	39%	40%	40%	64%	44%
INDS	61%	24%	92%	63%	53%	49%
INDIA	53%	49%	80%	87%	95%	56%

- Very low scoring on all (or nearly all) metrics
- Entrepreneurial indicators: higher for individual than institutional (a lot of under-supported talent)
- Capital: human, risk, finance all in short supply
- Quality of electricity system all weak
- household indoor air quality worse
- water system/quality also worse
- Energy access an issue, Argentina is a net energy exported, though 12% of its population have no access to electricity

Conclusions

This work has used a diverse spread of metrics to analyse the energy innovation systems of 39 OECD and non-OECD countries. The data supports a general conclusion that countries with more developed and robust economies tend to have more advanced and developed energy innovation systems. The data enables assessment of both the overall performance of countries and of individual factors in the functioning of their energy innovation system.

There are many exceptions to the general conclusion that countries with more developed and robust economies tend to have more advanced and developed energy innovation systems: there are many different ways that economic and environmental factors can align or conflict and a simple ranking scale cannot capture this diversity. Indeed, it can give the false impression that lower ranked countries should simply copy the characteristics of the top countries in order to develop top ranking countries themselves. To overcome this simplification, the initial were used to classify the type of countries into 7 categories that capture structural and distributional differences in energy innovation system performance.

Since some of the data used is from sources not intended as an energy innovation system assessment (though the data is relevant to the functioning of the energy innovation system), some of the analysis is considered a meta-analysis, and caution is exercised when drawing conclusions.

A number of very preliminary conclusions can be drawn from the analysis to date:

The importance of a long-term plan: countries that have successful energy innovation systems tend to have long-term plans for decarbonizing their energy system. More research is needed to identify if certain characteristic make for a better or worse plan, but the absence of a plan can lead to policy uncertainty and instability, which undermines long-term investments and can impact competitiveness (cost of energy transition isn't negligible, but alternative of no plan can be expensive).

The importance of entrepreneurship: the impact of entrepreneurship on the energy system has not been directly measured in this analysis, but it does appear to explain why certain countries that make large investments in energy R&D (e.g. Japan & Korea) are poor at commercialisation. This is an area needing further investigation, but it is significant that a country with high R&D expenditure and high entrepreneurship scores (USA) was the source of the hydraulic fracturing innovation that has led to such changes in the global gas energy market.

Importance of understanding challenges for different types of countries: the categorisation of countries in this analysis have contributed to a preliminary classification for transition and energy innovation system types. While certain countries are leaders in terms of technology development (e.g. Denmark, Germany), other countries who are strong followers (e.g. Ireland, Portugal) should perhaps consider adaption and adoption a strength and orient their energy systems in this direction, rather than aspiring to be leaders. There will be different challenges for countries that are leaders, early followers and late followers. Given how few countries in the world can feasibly be leaders and how many must by definition be some class of follower, the follower country innovation system is an area worthy of more research. It also highlights the role of a standard design and international networks and collaboration.

Governance challenges: in line with findings from other researchers, there are high governance requirements for the energy transition. This is particularly challenging for countries with weak governance and institutions for whom the energy transition will be most radical. This is also an area for further research.

Lock-in: lock-in is a very well-known challenge to anyone researching the energy system. This analysis has indicated that countries with low (but not no) energy reserves are more likely to be advanced in the energy transition than countries with large energy reserves or countries with no energy reserves. For countries with large fossil fuel reserves, there is clearly an energy tax lock-in. The challenges of imagining how countries with large fossil-fuel reserves will transition is one worthy of more research.

References

Gallagher, Kelly Sims, Arnulf Grübler, Laura Kuhl, Gregory Nemet, and Charlie Wilson. 2012. "The Energy Technology Innovation System." *Annual Review of Environment and Resources* 37 (1): 137–62. doi:10.1146/annurev-environ-060311-133915.

IPCC. 2014. "CLIMATE CHANGE 2014 -Synthesis Report." IPCC.

Mads Borup, Antje Klitkou Maj Munch Andersen Daniel S Hain Jesper Lindgaard Christensen and Klaus Rennings. 2013. "Indicators of Energy Innovation Systems and Their Dynamics," November, 1–74.

Appendix

Overview of indices used in this analysis

The *Global Innovation Index (2014)* "is the result of a collaboration between Cornell University, INSEAD [a high profile business school], and the World Intellectual Property Organization (WIPO)" and "covers 143 economies around the world and uses 81 indicators across a range of themes" that include institutions, human capital and resources, infrastructure, market sophistication, business sophistication, knowledge and technology outputs, and creative outputs (Cornell University et al., 2014).

The *Global Competitiveness Index (2014)* "is published by the World Economic Forum". With input "from 160 Partner Institutes worldwide", it measures the "competitiveness performance of 144 economies" under a range of indicators including institutions, infrastructure, macroeconomic environment, health and primary education, higher education and training, goods market efficiency, labour market efficiency, financial market development, technological readiness, market size, business sophistication, and innovation (Schwab, 2014).

The *Global Entrepreneurship Index (2015)* is published by the Global Entrepreneurship and Development Institute to "measure the quality and the scale of the entrepreneurial process in 130 countries around the world" by gathering data under the broad headings of entrepreneurship attitudes, abilities and aspirations (Ács et al., 2015).

The *Environmental Performance Index (2014)* is a "joint project between the Yale Center for Environmental Law & Policy and the Center for International Earth Science Information Network at Columbia University" that "scores country performance in nine issue areas" which are health impacts, air quality, water & sanitation, water resources, agriculture, forests, fisheries, biodiversity & habitat, and climate & energy (Hsu et al., 2014).

The *Energy Sustainability Index (2014)* is published by the World Energy Council and "provides a comparative ranking of 129 countries" that "highlights how well countries manage the trade-offs between the three energy sustainability dimensions" of energy security, energy equity and environmental sustainability (Wyman, 2014).

The *Cleantech Innovation Index (2014)* is published the Cleantech Group and the WWF; in the words of the report, "40 countries were evaluated on 15 indicators related to the creation, commercialisation and growth of cleantech start-ups" (Cleantech-Group, 2014).

Correlation of indices in final results

Table 11 – Indicator correlation scores

Indices		Correlation
Entrepreneurship	Innovation	0.78
Energy	Environmental	0.65
Competitiveness	Innovation	0.64
Environmental	Entrepreneurship	0.64
Cleantech	Innovation	0.62
Environmental	Innovation	0.61
Cleantech	Competitiveness	0.55
Energy	Innovation	0.53
Energy	Entrepreneurship	0.45
Entrepreneurship	Competitiveness	0.42
Cleantech	Entrepreneurship	0.38
Energy	Competitiveness	0.35
Environmental	Competitiveness	0.3
Cleantech	Energy	0.29
Cleantech	Environmental	0.15