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Using Emissions Intensity to Better Track Energy Transitions

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Abstract **– Current metrics fail to adequately capture the temporal and spatial complexity of energy transitions in a sufficiently meaningful way and this limits their usefulness to inform effective climate and energy policy and management. In this paper we propose a cumulative integral of CO_2 emissions intensity for electricity and heat use as a metric to monitor energy transition progress. We demonstrate its application using International Energy Agency data for each of the G20-member countries. Findings show that whilst most countries are far from the energy transition positions required to effectively mitigate climate change, there are some examples of countries that have made an effective transition that provide useful insights into how energy transitions might progress more extensively.**

Keywords **– Climate change mitigation; energy transition; emissions intensity.**

1. INTRODUCTION

Writings on modern 'energy transitions' began following the oil crisis of the 1970's and the development of improved understanding of the role of fossil fuel burning in climate change. Early climate research by Williams [1] and Bach [2] reference the role of fuel burning in climate impacts, and work by Hayes [3] highlights the need to move on from petroleum dominated energy profiles. More recent work focuses on technological change and the temporal dynamics of transition, with a growing consensus and discourse around the urgency and necessity for climate stabilisation [4]–[7].

A developing body of literature now promotes and supports energy transition research, driven by the growing recognition of the necessity for change [8], including elements of economics, social science and engineering. In a recent review, Sovacool and Hess [9] noted 96 theories on energy transitions from 22 social science subdisciplines. These theories are distinct from those in the 'innovation' field of study which have been dominated by neoclassical and evolutionary economics perspectives. Examples of these approaches are presented by Grubler [10], who offers a historical record of transition research along with insights into transition drivers and dynamics drawn from this legacy, or Wilson and Grubler [11], who frame two global historical energy transitions in terms of the technological change patterns. Foxon [12] argues the benefits of a co-evolutionary framework to bridge the ecological economics, while Lane *et al.* [13] applies a technological approach, using engineering capacity to discuss the constraints associated with sustainable energy transition. Hansen and Coenen [14] frame sustainable transitions as geographic processes, providing a survey of the influence of place in other studies.

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In our summation, the current literature on energy transitions can be organised into two paradigms; one which we describe as 'reflective' and the other as 'expectant'. The reflective approach documents historical transitions as price-driven events, which by definition occur over decades to centuries [6], [10], [15]–[16]. These theories posit that techno-economic rationales require transitions to be protracted, gradual affairs. This is substantiated by a broad range of significant historical evidence, and the common characteristics and analysis of previous energy transitions.

The 'organic' paradigm is captured by the likes of Solomon and Krishna [17] and by Sovacool [18]. The latter specifically challenges the dominant neo-classical view of energy transition, suggesting that the temporal dynamics of modern energy transitions are adaptable and even elastic, as they are driven by a completely different set of pressures and motivations from their historical precedents. Overall, these works expand the scope of investigation to include innovative and even optimistic views of the potential for stationary energy systems to mitigate climate change. This interpretation has been applied and expanded by other researchers (for example, Kern and Rogge [4] and Bromley [7]), who reference Sovacool as starting valuable debate into energy transition dynamics.

'What gets measured gets managed' may be a cliché, but there is nevertheless value in the combination of transparent reporting, simple yet informative indicators, and appropriately targeted accountability to focus decision making and resource allocation. In this paper, we advocate for the adoption of a consistent metric in the identification and tracking of energy transitions. In presenting our model, we hope to promote 'energy transitions' as a stand-alone discipline and encourage discussion around its unique characteristics. By opening a dialogue around the quantitative measures and definitions of modern energy transitions, our goal is to attract critique to refine the concept to help inform better climate and energy policy, and by doing so promote scientific progress in the research area.

2. BACKGROUND

Analysis of energy transitions are by definition retrospective. Most commonly, the diffusion of an individual fuel type or technology in a given location is expressed as a percentage of total output. Traditional analysis relates the market share or diffusion of a studied feature as a distinctive S-curve, with observation of time between recognised thresholds, for example 1 %, 10 %, 50 %, 90 % and 99 % [6], [10], [19].

Building on this, Araújo [19] helpfully observes energy transitions with regard to scale, structure, and quality; where scale is the growth and/or absolute consumption of a variable as an input or output, structure is the proportional contribution of a specific variable (expressed as a percentage), and quality is the assessment (singularly or as a trend) of efficiency, reliability, sustainability or other aspects representing the performance of the system. An excellent example of this is provided by Rozentale and Blumberga [20], who apply weighted (qualitative) criteria to evaluate the impact of various Latvian energy policy elements on climate.

The complexity around such quantifications cannot be understated. Analysis is dependent not only on the quantity of data available, but also the consistency and quality of that information. Variables such as fuel heating values, timescale and scoping (gross generated vs. net consumed) are not always obvious or assessable. These distinctions may be more exaggerated when considering historical data or data from underdeveloped regions.

Historical scales depend on the dominance of a single fuel source or prime mover to define and quantify the change from one prevailing system to the next. This is unlikely to be applicable for the next energy transition, where a range of efficiency, renewable and low emission solutions are to be expected. This is relevant both for developed economies which may use efficiency gains and lower emission fossil fuels as an intermediary step to a renewable dominant system, and for developing energy systems as user demand and technological agency matures. As noted by Abdollahi [21], energy use and economic growth are found to be bidirectionally causal, as are CO_2 emissions and economic growth in developing countries.

Using existing assessment techniques, aggregation of results is likely to be necessary. This may invite scope or dependability issues if methodology is not applied consistently across fields. Alternatively, application of a custom metric which is able to capture these complexities will better reflect the intended outcomes of sustainable energy transitions. Therefore, we suggest that carbon intensity (expressed as units of carbon dioxide, CO_2 per MWh or per GJ for example) may provide an appropriate quantitative metric to assess the progression of a sustainable energy transition within bounded energy systems.

To highlight the potential application and usefulness of this metric, we have considered its application against both an 'accepted' and a contentious transition event, as well as a 'reverse' or 'unsustainable' transition.

The dominance of nuclear power in the French electricity system is well established. This transition to a nuclear dominated electricity profile was driven by the impacts of the 1970's oil shocks and a need to increase energy independence for the country. It is often cited as an example of rapid transition and even Grubler *et al.* [22] concede its validity (although one driven by specific policy rather than market forces). International datasets curated by the International Energy Agency [23] show the change in nuclear contribution between 1970 and 1990 to be an increase of 4 % to 74 % for a net increase of 70 %; however, emissions intensity over the same period decreased by a larger 78 %. The setting of the nuclear 'revolution' within a larger energy security policy context makes the emissions intensity transition greater than that of the technology alone, highlighting the importance of sectoral scale approaches to data, rather than the fuel or prime mover focuses which have been emphasized in technological transition literature.

This metric also holds potential for secular assessment of more provocative transition examples. Perhaps the most contentious is the example offered by Sovacool [18] is for the uptake of alternative and flex-fuel vehicles in Brazil. His application of new automobile sales post Proálcool suggests transition occurred over a 6-year period beginning in 1975, achieving 90 % of new purchases at the end of that timeframe. While this example was strongly rebuffed by Grubler *et al.* [31] for representing changes in flow rather than stocks, such a significant change may well signify a transformation in consumer behaviour or industry preferences. Rather than argue the validity of the example, it may potentially be more useful to consider any material changes in the output which resulted.

Fuel use data provided by the Brazillian Ministério de Minas e Energia/Ministry of Mines and Energy and Empresa de Pesquisa Energética [24], along with industry standard emission intensity default values, show the sectoral emissions intensity change from the 1970 baseline. These reductions peak in 1990 with an 18 % decrease and decline from there (12 % in 2000, rebounding to 17 % in 2010). By applying emissions intensity of the primary energy to this example, we show its capacity to provide an impartial assessment of impact, removed from the contention present with more flexible metric options.

The metric also holds with 'regressive' transition events. Between March 2011 and May 2012, Japan gradually shut down each of its 50 remaining nuclear reactors following the tragic Tōhoku earthquake and subsequent tsunami. Approximately 30 % of Japan's generation capacity, or over 44 300 MW, was taken offline. This shortfall was made up through a combination of austerity measures, demand-side management and supplementary supply from higher emission energy sources. While not widely recognised as a transition event, the episode has been framed in this way by both Wakiyama *et al.* [25] and Hermwille [26].

Emission intensity data from the IEA [27] shows the average emissions intensity in Japan from 1990 to 2010 was recorded as 434 g CO_2 per kWh of electricity and heat (with a minimum of 402 g CO_2/kWh during this time). By 2013 this was calculated to have increased to 568 g CO_2/kWh; representing a 30 % increase over the pre-disaster average. This shows the potential of emissions intensity to identify and track 'regressive' transitions in additional to sustainable ones.

To apply the emissions intensity metric to the 'fundamental shift' required in our energy systems, it must be applied to what an ideal 'transition scenario' would entail, how this would be represented by the selected metric and how performance can be critically assessed. In our view, a sustainable energy transition should have the following features:

- Direction – a continuing reduction in emissions, rather than increase or oscillation;
- Magnitude – a significant reduction; with the larger reduction improving the overall assessment result;
- Rapid – the faster the reduction the lower the resultant emissions and the better the score;
- Efficient Pathway – ideally a concave rather than convex pathway to reduce total emission loads.

All these criteria will be reflected in the shape of the emissions intensity trend, and can therefore be assessed by measuring the area under the line. The greater, faster, more efficient pathway will produce a smaller area than its modest, slower, less efficient partner, even when beginning and ending at the same point. Further, the process holds for a number of theoretical trends and energy intensity outcomes, including theoretical negative emission scenarios.

The use of an integral, rather than individual intensity trends, allows comparison of multiple assessment candidates, provided that consistent timelines are applied. The selection of the timeline will be critical, as the results are highly dependent on this input. Review can therefore be targeted to a selected horizon (such as the implementation of an international agreement), or expanded to account for historical performance which is relevant to discussions of energy equality between economically developed and developing nations, or grandfathering arrangements.

3. METHODS AND PROCEDURES

Annual data for gross electricity and heat production (converted to TJ) and corresponding sectoral Carbon Dioxide emissions (as Mt of CO_2) were collated from the subscription IEA [23], [28] research datasets. For OECD countries data was generally available from 1960 onwards, with others beginning in 1971. The bulk of non-OECD countries was provided from 1971, with the balance (excepting political unrest etc.) provided from 1990. The 1971 starting point was selected to maximise the coverage of the assessment and provide some recognition of the diverse economic development timelines of the candidates.

The resultant kT/TJ values were checked against equivalent data provided by the IEA as gCO_2/kWh for consistency, and found to be comparable once converted to consistent units. The average difference between values was found to be 0.111 % across the global dataset. Values for the G20 members was extracted for analysis. Data was taken from a consistent 1971 baseline, which meant Russia was excluded due to a lack of information.

Emissions intensity was then integrated over time according to Eq. 1:

$$\mathit{Cumulative\,Integral} @ \mathit{time}\ T = \sum_{i=0}^{T} \frac{(y_i + y_{i+1})}{2}(x_{i+1} - x_i)\,, \tag{1}$$

where
- y emission intensity;
- x calendar year;
- i the number of reporting cycles or intervals (in this case, annually) which have elapsed.

For this assessment x_0 is 1971 and 2017 represents x_{46}.

The cumulative integral for each G20 member was then converted to a score out of 100 for ease of assessment. This was completed by setting the maximum integral at 100, with each country provided a result based on its proportional performance within the cohort.

4. RESULTS

Analysis reveals that of the G20 members included in the cohort, Australia, Indonesia and South Africa have the slowest transition progress, while Brazil, Canada and France are the best performing (are the closest to / have achieved a sustainable energy transition, by a clear margin) (Table 1).

TABLE 1. CALCULATION RESULTS FOR CUMULATIVE INTEGRAL OF G20 CO_2 INTENSITY ELECTRICITY & HEAT SECTOR

	CO_2 Emissions Intensity Cumulative Integer 1971–2017	**Transition Progress Rank for Cohort**	**2017 Emissions Intensity, kg CO_2/GJ**
Brazil	1029	9	32
Canada	2424	20	39
France	2569	21	21
Argentina	5331	44	97
Italy	6029	50	84
Japan	6110	51	143
Mexico	6771	56	133
Turkey	7215	60	124
Germany	7335	61	108
Korea	7445	62	141
United States	7539	62	115
United Kingdom	7753	64	68
India	9257	77	200
People's Republic of China	10 086	84	162
Saudi Arabia	10 794	89	172
Australia	10 934	91	206
Indonesia	11 358	94	213
South Africa	12 064	100	245

The cumulative integral of these countries was less than a quarter of the highest emission-intensity results, with a large disparity between these results and the remainder of the group, with the next highest score (Argentina) being over double the proceeding one. The results show a strong skew towards the higher integer scores, and therefore higher emission intensity for electricity and heat production. The two single largest GHG emitting nations, USA and China, also appear within the higher quadrants. A more complete representation of individual country performance is provided by Fig. 1.

As would be expected, the trend is identified that those countries with lower transition scores have a higher proportion of renewable and zero emissions electricity and heat production, with a general decrease moving towards the higher transition scores. However, as the metric is cumulative, the dominant influence is the historical emissions intensity. This means that a historically low or high emissions intensity is more important to the result than modern performance (in isolation). Adjusting the time scale of the analysis (for example, to a five- or ten-year horizon) would provide a different outlook.

The focus of the metric is to gauge relative transition progress. As such, little correlation is observed between absolute emissions and emissions intensity. A large emission-efficient sector is favoured over a small inefficient one, but cannot account for the productivity in the application of that energy (that is, work performed for that input). For example, Korea and the United States both returned scores of 62, despite Korea's CO_2 intensity being higher both at start and finish of the study period, as the United States emission intensity increased in the late 90's making a convex curve compared to Korea's more concave shape.

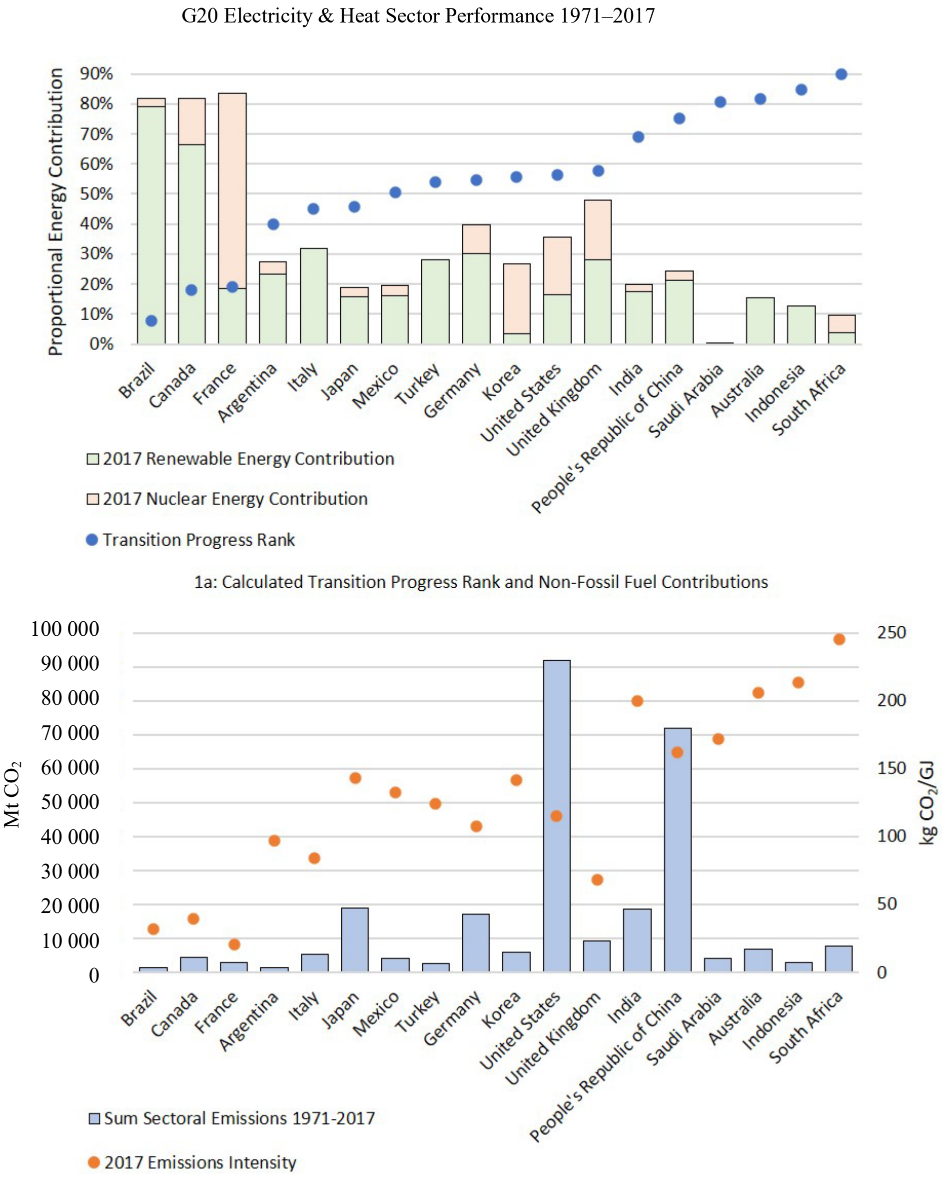
5. DISCUSSIONS AND CONCLUSIONS

The results show that emissions intensity provides a valid preliminary metric for the analysis of energy transitions. Measuring the state of energy transition as a cumulative integer (and conversion to a comparative performance value) provides a simple, quantitative score for monitoring and tracking of performance. A business-as-usual baseline could also be established to provide a consistent benchmark score for assessment of improvement. Integrating a target intensity, such as that provided by Rogelj *et al.* [29][†] could provide a future-cast integer against which policy and performance could be measured.

The limitations of the technological bias in this approach are not unacknowledged. As championed by Hirsh and Jones [30], energy transition includes a social dimension that cannot be reflected by standard quantitative metrics, and Grubler [10] emphasis the advantages of an inclusive approach considering energy services, efficiency, costs and trends. This metric unfortunately cannot satisfy this criticism, and remains an output-based approach. However, perhaps by expanding the measurement baseline to an emissions-centric approach, additional data collection can be explored and promoted for future advancement.

Our results show that all but three of the G20 members analysed are making insufficient progress to transition their energy systems to mitigate climate change effectively. However, it also shows clearly that there are established and growing economies with electricity sectors which offer both a technological and political template for achieving and sustaining low emissions energy profiles.

[†] Rogelj provides an electricity specific model consistent with a post-industrial 1.5-degree warming scenario. An emissions intensity of between -9.6 and 15.8 kg CO_2 per GJ has been modelled for a 2050 horizon.



1a: Calculated Transition Progress Rank and Non-Fossil Fuel Contributions

1b: Electricity and Heat Emissions Intensity and Total Historical Emissions

Fig. 1. G20 Electricity and Heat Sector CO_2 Intensity Analysis Results by Country.

While emissions intensity cannot tell the whole picture of the state of transition of an energy system (as it is possible to have a declining intensity and growing absolute emissions release), there are several advantages to using an emissions intensity-based metric. From a methodological point of view, it allows for consistent comparison of fleet performance and transition tracking through a single metric, without the complex structuring of multiple generation technologies and fuel types which typified historical transitions under energy monocultures. This method is agnostic to the technology and energy-source mixture of each individual system.

Energy transitions need to be focused on curtailing GHG emissions radically and rapidly. The performance of the majority of the G20 members to date has been woefully inadequate in this regard. Emphasis needs to be placed on how the 'whole' of our energy profile performs, not just efficiency gains for new build. This approach is best supported by forcing this rationale to the forefront of reporting and goal-setting, which can be assisted by prioritising an emissions intensity metric. Including historical performance within the assessment strengthens acknowledgement of the energy equality issues that need to be addressed concurrently with the climate emergency.

Renewable and lower-emission installed capacity is only impactful if generation from these sources is prioritised to displace more polluting sources. Using an intensity value simultaneously reflects efficiency improvements for cleaner generation technologies within existing fleets, and accounts for a multitude of emerging spatially and temporally diverse generation sources, without significant changes in established measurement technology and methodology.

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