On the emergence of the energy transition

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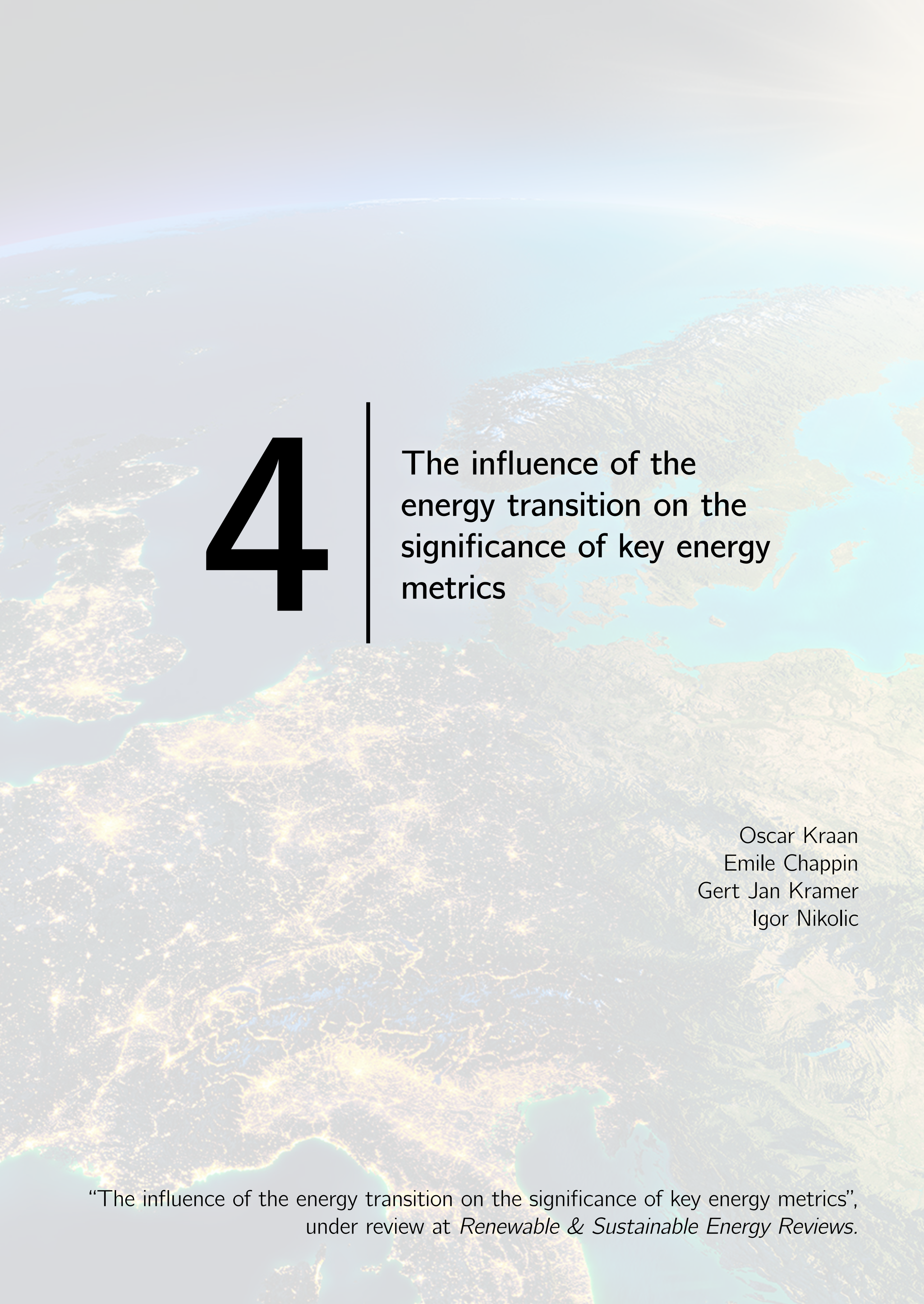

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The influence of the energy transition on the significance of key energy metrics

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Abstract

Transparent, consistent accounting of climate-related energy targets is a fundamental building block to the architecture of international climate agreements. Many of these climate targets focus on the transition of the energy system which has led to the development of various energy transition scenarios. Now that fossil resources are being replaced by non-combustible and renewable energy sources a re-assessment of the applicability of the current set of metrics on which these energy scenarios are based is necessary.

Now that energy derived from renewable and non-combustible resources with abundant availability but limited instantaneous availability becomes more prominent the ongoing electrification of the energy system combined with the decarbonisation of the electricity system has caused the current set of energy scenario metrics to become ambiguous. More specifically we show that Total Primary Energy (TPE) and its related indicators, Energy Efficiency (EE), Energy Intensity (EI) as well as the key metric Electricity Generation Capacity (EGC) have become unrepresentative, potentially misleading and for a large part irrelevant. This is problematic as these metrics steer climate policy and investment decisions based on statistical artefacts rather than valid representation of the energy system. This study concludes with a set of requirements on energy scenarios to overcome these problem that will lead energy scenarios to focus on Total Final Consumption within a mix of related energy metrics.

Keywords

Energy transition, Energy metrics, Decarbonisation, Electrification.

4.1 Introduction

Since the energy system is the largest contributer to the world's greenhouse gas emissions [206], decarbonisation of the energy system is key to limit global warming to 2 °C. Especially now that international negotiations [207] to limit global warming depend on National Determined Contributions (NDCs) [208], consistent, transparent accounting of these different targets and commitments becomes increasingly important.

Many of these NDCs depend on or make reference to (energy) scenarios [209] which are quantified narratives of future pathways [210]. These scenarios are often based on extrapolations of historical relationships collected in energy balances. Only four organisations [106, 211, 31, 212] publish these (historic) energy balances [213], whereas many more publish scenarios (e.g. Shell [7], Greenpeace [15], International Institute for Applied System Analysis [214], World Energy Council [215]). These scenarios help policy makers and many different societal stakeholders to debate policy options, monitor policy effectiveness and discuss trade-offs between various technology, system and value chains. Moreover, they support investors to make informed strategic decisions in an uncertain future.

These policy targets as well as scenarios are based on various metrics, such as *Total Primary Energy* and *Total Final Consumption* amongst others. An adequate, relevant and representative set of these metrics is of vital importance; they must be sufficiently broad to characterise the system, relevant for policy and business decision making and concise enough to facilitate smooth communication with and between (non-)experts. Here two kinds of metrics can be distinguished. The first are primary metrics which are absolute values (e.g. Total Primary Energy and Total Final Consumption). The second are indicators which are relative, typically ratios of primary metrics (e.g. Energy Intensity, Energy Efficiency).

4.1.1 Metrics and transition dynamics

With the effect of climate change becoming more evident, stakeholder's interests (i.e. objectives of policy makers, opportunities and risks for businesses and the general public) have changed. Where previously policy targets and business strategies were focused on the depletion of (fossil) resources, in the last decades there is increased focus on the impact of the use of resources. Moreover, where previously the total resource availability was of concern (i.e. oil, gas and coal reserves), presently the instantaneous energy availability is of primary concern (wind and solar radiation), marking a shift from Joules of primary energy to Watt hours of final energy.

Now that the energy transition progresses, the resource mix of the energy system changes and energy from non-combustible sources (i.e. wind, solar) becomes more prominent. These "new" resources are different from fossil fuels in two fundamental aspects: they are abundant rather than scarce but their instantaneous availability is limited, rather than being dispatchable on demand. Furthermore, two major developments in the energy system are ongoing: i) ongoing electrification of end use and ii) the decarbonisation of the energy system. We will show that these developments in combination with the fundamental differences with regards to the resources they rely upon, cause two key primary metrics to become impaired: Total Primary Energy (TPE) and Electricity Generation Capacity (EGC). Related indicators derived from these primary metrics, i.e. Energy Efficiency (EE) and Energy Intensity (EI) are also affected.

The source of these problems lies in the difficulty of finding a representative quantification of the energy system via an appropriate accounting method while the system is structurally changing. How do you account for the Joules contained in a barrel of crude oil and the kWh of electricity from a solar panel in a single metric?

Although often the explanation of the different possible accounting methods used for these quantifications are buried away in appendices [213, 216, 217, 218, 219], several researchers have mentioned the associated problems of accounting of energy metrics. Giampietro and Sorman [220] question the overall usefulness of energy statistics, and subsequently [221] argue to focus on a broader set of metrics instead of a "one size fits all" approach. Also Wang et al. [222] mention the difficulty of accounting for primary energy. Segers [223] advocate the use of an accounting method that compares renewable energy sources with typical conventional energy sources using a substitution method. Harmsen et al. [224] discuss the relationship between two policy targets, Europe's 2020 renewable energy target and it's 2020 energy efficiency target, and show that, depending on the accounting method used, renewable energy contributes very differently to the energy efficiency targets. Ligtfoot [225] also recognised the different accounting methods and concluded that primary energy values from various organisations are not comparable and the IPCC has insufficiently addressed this issue. In a comprehensive review Macknick [226] analysed discrepancies between data sources and recognised the differences resulting from different accounting methods. Also various reports from consultancies [227], governmental bodies [228] and other independent organisations [229, 230] including the IPCC [218] highlight the difficulty of comparing data from sources that use different accounting methods. To overcome these problems the United Nations in 2011 have published the International Recommendations for Energy Statistics [219] but universal implementation of these recommendations is far from reality.

Building on these long-recognised concerns of energy accounting, in this article these problems are put in the context of the fundamental dynamics of the global energy transition. We highlight statistical artefacts of the various (recommended) accounting methods that should be of concern to those that work with these metrics. We show how these developments relate to the architecture of climate change negations, and show how expected future developments will increase these problems. We furthermore make the connection between various energy metrics that are affected and show how set policy targets can interfere with international agreed goals to limit global warming.

This analysis is relevant as the consequences of these identified problems can be large. Many international regulations and targets depend on these metrics (e.g. European Directives [231, 232] and NDCs [208]): Thirty-five countries have set their NDC targets for climate change mitigation in terms of energy metrics [233]. For example, China, the singles largest emitter in the world [210] has set it's NDC in terms of TPE, India, the third largest contributor, has set its target in terms of EGC. Moreover, 143 of the 162 submitted NDCs mention energy efficiency [233]. In addition, many NDC targets are set relative to a baseline scenario. Which bring us to energy scenarios; although comparisons from different sources gives depth to the discussion on the different assumptions in these scenarios and to the robustness of results, comparing scenarios has become a near impossible. Together the in-transparency of documentation and unfamiliarity with this issue can lead to misinformed arguments and misguided policy choices. An assessment of an adequate set of metrics therefore becomes increasingly important.

We argue that the complex transition of the energy system, will need a diverse set of metrics to represent the system and build policy upon. However, adverse effects of accounting artefacts have to be prevented. Therefore, whereas previously energy scenarios focused on resource availability and thus on TPE within such as set, we propose to focus on Total Final Consumption instead as we will show that this metric gives a better representation of the current and future system, is more relevant with regards to policy targets and most importantly, thus not faces the issues of un-representativeness of TPE.

The organisation of this article is as follows, the use of Total Primary Energy and its related indicators Energy Efficiency and Energy Intensity will be discussed in Section 4.2. In Section 4.3 Electricity Generation Capacity will be discussed. A reflection on our findings is presented in Section 4.4 and conclusions are laid out in Section4.5.

4.2 The use of Total Primary Energy

To introduce the different ways to represent the energy system let's look at the main metrics of energy scenarios. Energy scenarios are composed of three main metrics:

Energy Services (ES): The demand for a particular energy service such as passenger kilometres, tonnes of steel etc.,

Total Final Consumption (TFC): The consumption of energy carriers such as solid, liquid or gaseous fuels and electricity to fulfil this service demand

Total Primary Energy (TPE): the primary energy required to produce these energy carriers.

These three metrics are connected subsequently by the energy service efficiency and the production efficiency, see Figure 4.1.

Figure 4.1 – Primary energy metrics and efficiency indicators. Energy services by sector need to be supplied by energy carriers which need to be produced from energy sources.

TPE has long been central to energy scenarios as the availability of energy resources was of main concern to policy makers and business decision makers. During the last decades in which the energy system was dominated by the use of combustible resources such as fossil fuels and biomass, its definition was relatively straightforward: "energy that has not been subjected to any conversion or transformation process" [234]. This was supported by the fact that the primary energy content for combustible resources such as fossil fuels and biomass, is easily measured and commonly tracked.

Calculating the primary energy equivalent for non-combustible resources such as wind, solar photovoltaic (PV), nuclear, hydro and other marine-based technologies, is not self-evident because it's primary energy equivalent is not consistently defined and not widely measured. Figure 4.2 shows the different energy sources and how they can be differentiated over renewable versus non-renewable energy sources, and combustible versus non-combustible sources. The dark grey area indicates sources that produce electricity; the lighter grey area indicate sources that produce heat as an intermediate step.

Different organisations use different approaches to calculate the primary

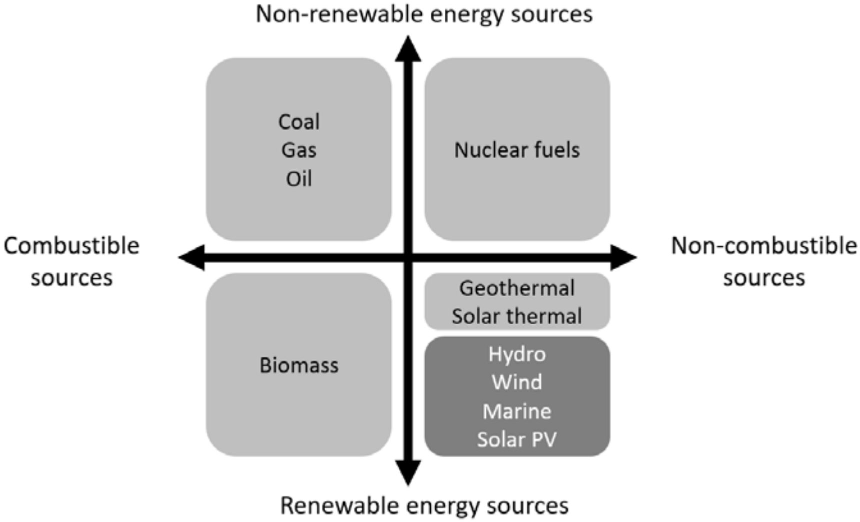


Figure 4.2 – Primary energy sources. Light grey areas indicates sources with heat as conversion step. Dark grey indicates sources that directly produce electricity. Marine includes wave and tidal energy, Wind includes off- and on-shore wind, Solar PV (Solar Photovoltaic).

energy equivalent of non-combustible energy sources, but in general four approaches can be distinguished (see Table 4.1).

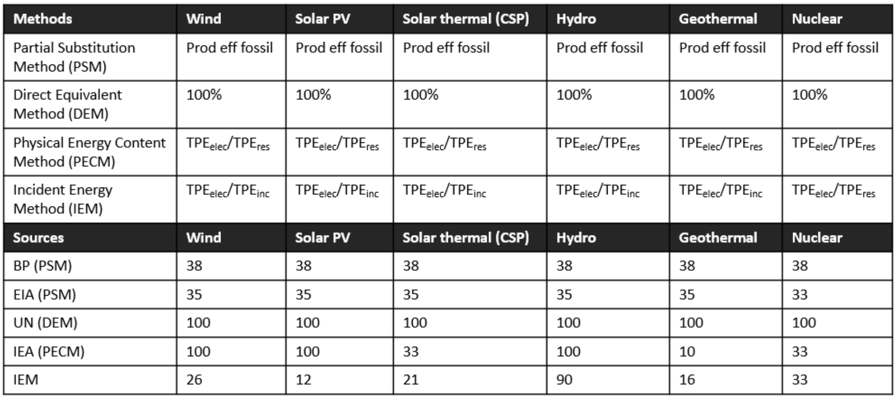
Partial Substitution Method (PSM); EIA, WEC, IIASA, BP. With this method the primary energy equivalent for non-combustible energy sources that produce electricity, is defined by the hypothetical amount of energy it would require, on average, to produce an equivalent amount of electricity in a thermal power station using combustible resources. In practice this means that a representative efficiency of thermal power stations is used to calculate the primary energy equivalent for non-combustible resources. This method is widely used by for example BP [106] the World Energy Council [235] and IIASA [213]. The fundamental difficulty with the partial substitution method is that it does not have a physical basis, does not represent any real market quantity and assumes a hypothetical and arbitrary defined conversion loss. This method is even more problematic when renewables begin to displace other renewables (instead of fossil fuels). Moreover, in energy system that are dominated by renewables, (e.g. hydro-electricity dominated countries such as Norway), this method gives a distorted view on the reality of the system as its representation is based on thermal generation (with relative low conversion efficiencies) while in reality the system is based on non-combustible sources.

Direct Equivalent Method (DEM); UN, IPCC. With this method the primary energy for non-combustible energy sources is set equal to the energy contained in the produced electricity. This approach excludes the production efficiency of conversion technologies such as solar panels (from solar radiation to electricity) or wind turbines (from wind to electricity) and implies that the conversion of non-combustible renewable energy is 100% efficient. This method is also often used, for example by the United Nations Statistical Bureau [217] and in IPCC reports [218]. The problem that arises from the use of this method is that a statistical defined 100% efficient production efficiencies makes primary energy for these sources a statistical artefact. It does not measure a characteristic of reality, but gives a statistical representation of reality to be able to add up the many different sources the energy system relies upon.

Physical Energy Content Method (PECM); IEA, OECD, Eurostat This method differentiates the non-combustible resources in resources that produce heat as intermediate step (i.e. nuclear, solar thermal and geothermal energy sources) and those that do not (wind, photovolataic), see Figure 4.2. For technologies that produce electricity directly, the method accounts for the generated electricity while for technologies that produce heat it accounts for the produced heat. Again, this method is widely used by various organisation, for example the OECD, IEA [236] and Eurostat [237] and is the basis of the International Recommendations of Energy Statistics [219]. This method can be confusing: for some technologies (i.e. solar PV, wind and hydro) the production efficiency is set to an arbitrary 100%, while for others (i.e. solar thermal, geothermal and nuclear) much lower efficiencies (as low as 10%) are used although both are based on renewable resources that produce electricity. Additionally, for resources with an 100% production efficiency the same difficulties hold as described in the Direct Equivalent Method. Moreover, in this approach the share of renewable technologies that produces heat is over-emphasised as their primary energy equivalent is multiplied by their production efficiency and estimated at, in the case of solar thermal (i.e. concentrated solar power), ten times its electricity output. The same problem holds for electricity from nuclear for which primary energy equivalent is set at three times its electricity output. For some resources (i.e. wind, solar and hydro) this accounting method downplays their share in Total Primary Energy and an argument could be made that renewables may not be mature enough to deploy on larger scale.

Incident energy method (IEM) With this method the primary energy for non-combustible energy sources is defined as the energy that enters an energy conversion device. For solar this would be the energy that enters the surface of the photovoltaic panel or mirror, for wind the energy that passes the rotor disc, or in the case of geothermal, the energy contained in the hot fluid at the surface of the bored well. The difficulty with the incident energy approach is that renewable energy plants almost exclusively track electricity output and therefore this metric is not widely reported by organisations that produce energy balances.

Table 4.1 – Production efficiencies of non-combustible energy sources. Data from [106, 229, 210, 217, 216]



Methods	**Wind**	**Solar PV**	**Solar thermal (CSP)**	**Hydro**	**Geothermal**	**Nuclear**
Partial Substitution Method (PSM)	Prod eff fossil	Prod eff fossil	Prod eff fossil	Prod eff fossil	Prod eff fossil	Prod eff fossil
Direct Equivalent Method (DEM)	100%	100%	100%	100%	100%	100%
Physical Energy Content Method (PECM)	TPE_{elec}/TPE_{res}	TPE_{elec}/TPE_{res}	TPE_{elec}/TPE_{res}	TPE_{elec}/TPE_{res}	TPE_{elec}/TPE_{res}	TPE_{elec}/TPE_{res}
Incident Energy Method (IEM)	TPE_{elec}/TPE_{inc}	TPE_{elec}/TPE_{inc}	TPE_{elec}/TPE_{inc}	TPE_{elec}/TPE_{inc}	TPE_{elec}/TPE_{inc}	TPE_{elec}/TPE_{res}
Sources	**Wind**	**Solar PV**	**Solar thermal (CSP)**	**Hydro**	**Geothermal**	**Nuclear**
BP (PSM)	38	38	38	38	38	38
EIA (PSM)	35	35	35	35	35	33
UN (DEM)	100	100	100	100	100	100
IEA (PECM)	100	100	33	100	10	33
IEM	26	12	21	90	16	33

To illustrate the effect of these diverse definitions, Figure 4.3 shows the development of total primary energy under a single energy transition scenario but under different accounting methods, PSM, DEM and PECM. It's base scenario is Sky, Shell latest energy transition scenario [7] (compatible with the Paris Agreement). It is based on the World Energy Model [238] which uses IEA standards of measurement for all energy sources and carriers, and thus follows the PECM.

The figure shows that, although differences today are relatively modest, these differences are expected to increase in the future as increasing electrification and decarbonisation of the energy system make non-combustible zero-emission energy sources more prominent.

Figure 4.4 illustrates the effect on a country level. The figure shows the TPE figures for three countries with different energy system structures; France, The Netherlands and Norway. France in 2015 was dominated by nuclear energy (see pie charts), while The Netherlands was dominated by fossil fuels and Norway was dominated by renewables (especially hydro). The Figure shows that there are large differences between TPE figures, which also effects the relative share in the energy mix, especially for non-fossil dominated countries such as France

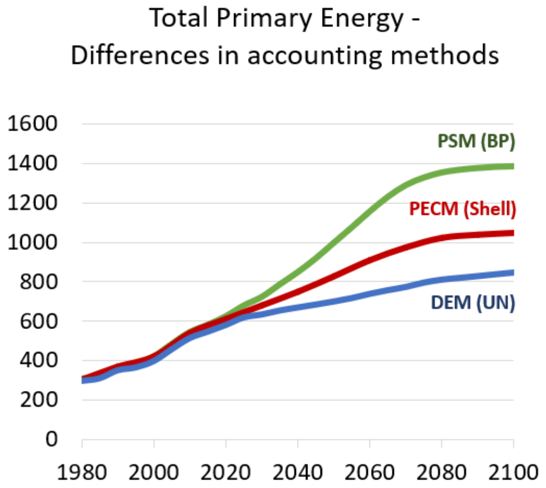


Figure 4.3 – Total primary energy of Shell's Sky scenario under different accounting methods. Comparison is made with production efficiencies from Table 4.1. Data from [7]

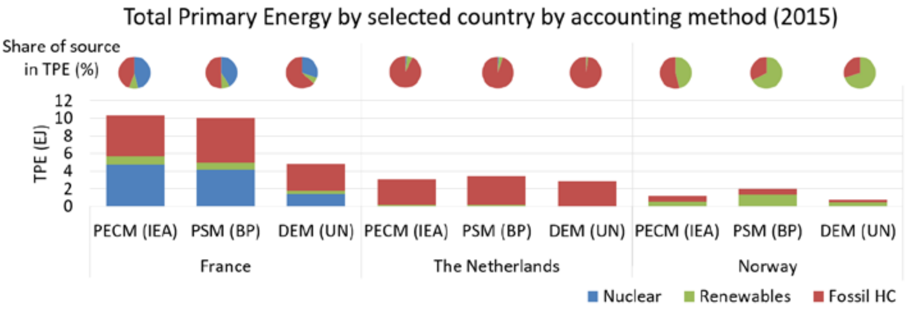


Figure 4.4 – Total Primary Energy by selected country by accounting method in 2015. Data from [31]

and Norway. Of course these differences originate from the different production efficiencies given in Table 4.1.

4.2.1 Direct effect

From this analysis we conclude that different TPE definitions lead to increasing ambiguity because of the following six reasons.

1. The use of production efficiencies of 100% for non-combustible energy

resources by many organisations makes primary energy for these sources a statistical artefact. It does not measure a characteristic of reality, but gives a statistical representation of reality to be able to add up the many different sources the energy system relies upon.

2. Now that abundant renewable resources are replacing finite fossil resources, the primary energy demand becomes increasingly less relevant.
3. TPE values depend largely on the applied accounting method which all face difficulties.
4. Within these approaches, organisations use various figures that are likely to change over time with technology improvement and system integration.
5. These problems are expected to increase over time as decarbonisation and electrification of the energy system will ensure that non-combustible resources will increase their share in the energy mix.
6. Climate change mitigation targets expressed as a reduction of TPE can result in an *increase* of GHG emissions under certain accounting methods (PECM) while they don't incentivise the use of renewable resources in others (PSM). Under PECM, an TPE reduction target would disincentivise the replacement of fossil generation by low efficiency, zero-emissions alternatives (i.e. replacing geothermal, solar thermal or nuclear with fossil generation).

The difficulty of defining TPE unambiguously makes it a misleading metric now that the energy transition progresses and stakeholders can choose an accounting method that is most attractive to them. This has significant adverse effect on the value of ability to set quantitative targets and the ability to compare them. Together this makes appreciations of targets, ambitions and progress defined in TPE difficult. Specifically, difficulty with comparisons arise with respect to the following:

1. **Scenarios** become difficult to compare when each scenario uses a different accounting method. This makes the discussion on underlying assumptions and narratives near impossible which impairs one of its main purposes; communication with and between stakeholders.
2. Comparing the efforts and targets of **countries** and the progress towards them becomes difficult as countries with a particular dominant energy source (e.g Norway with hydro) can be very differently represented under different accounting methods. This makes comparisons of these countries

with other countries depended on the used accounting method. As comparing countries becomes difficult, comparing policy targets such as NDCs also becomes difficult when different accounting methods are used. Ultimately this hinders progress on international climate negotiations.

3. The comparison of different **technologies** also becomes difficult. Various production efficiencies across technologies in the different account methods make the share of these technologies in the energy mix dependent on the accounting method. For example, TPE figures for concentrated solar power (solar thermal) using PECM or PSM give these technologies a much larger share compared to solar PV then if one would use the DEM. This can have consequences as targets set on TPE can lead to policy incentivising deployment of technologies based on a superficial representation of reality. From a climate-based policy target in general it us undesirable that one zero-emission technology will be promoted over another zero-emission technology solely based on accounting artefacts.

The number of different approaches combined with the expected increase of difficulties each approach faces, shows that TPE is at best an irrelevant and potentially a misleading metric to represent the energy system given the expected decarbonisation and electrification of the energy system.

4.2.2 Indirect effects on related indicators: Energy Efficiency & Energy Intensity

The consequence of the inconsistent definition of TPE is that related indicators, specifically, Energy Efficiency and Energy Intensity are also affected. This has consequences as EE and EI are both indicators that are widely reported, intensively studied and subject to various policy targets and business considerations. As mentioned in Section 4.1, almost 90% of the submitted NDCs mention energy efficiency [239].

Energy efficiency

Energy efficiency (EE) is defined as:

$$EE = \frac{Energy\ Service}{TPE} \tag{4.1}$$

Now that TPE becomes ambiguous, the indicator energy efficiency now also becomes difficult to appreciate. This becomes evident when the energy efficiency of a normal gasoline car is compared with an electric vehicle driving on electricity derived from non-combustible energy sources. Changing the supply of the energy service (in this case vehicle kilometres driven) from using a thermal power train to one without heat conversion can make relatively small differences (using a fossil equivalent efficiency for the production of renewable-based electricity via PSM) or dramatically increase the efficiency (using a 100% production efficiency of the renewable-based electricity via PECM & DEM). The same holds for electrifying heat demand in buildings (e.g through heat pumps); depending on the accounting method this can dramatically increase (using PECM & DEM) or barely change (PSM) energy efficiency of the building. In a general context this is relevant as efficiency targets are more or less easy to reach depending on the used accounting method.

Energy Intensity

The same argument holds for the indicator Energy Intensity. It measures the amount of energy that is used to produce an unit of GDP and is defined as:

$$EI = \frac{TPE}{GDP} \tag{4.2}$$

The energy intensity of a country can differ substantially depending on what accounting method is used. Iceland for example, is a leader in several energy savings programs but its energy intensity remains high in energy balances that use the PECM [240]. This can be explained by understanding that in PECM the production efficiency of electricity generation from geothermal sources which are increasingly deployed in Iceland, is relatively low (10%). Using a different, much higher production efficiency of up to 100% in DEM would lower its energy intensity dramatically.

Let's us consider again the three cases discussed in Section 4.2, France, The Netherlands and Norway. Figure 4.5 shows the energy intensity figures for these three countries in 2015. It shows that comparing these three countries, three different conclusions could be possible, dependent on the accounting method used. Either France, or The Netherlands or Norway has the worst energy intensity. In the next section we will argue that EI based on Total Final Consumption instead of Total Primary Energy is a better expression of energy intensity which is shown on the right-hand three columns in Figure 4.5.

4.2.3 Recommendations on the use of TPE, EE and EI

Given the shift of focus from resource use to climate change impact, policy targets have changed. To address climate change impact, a complex and comprehensive system transformation that covers many sectors and locations will be required. Setting, comparing and monitoring of targets relating to this transition therefore

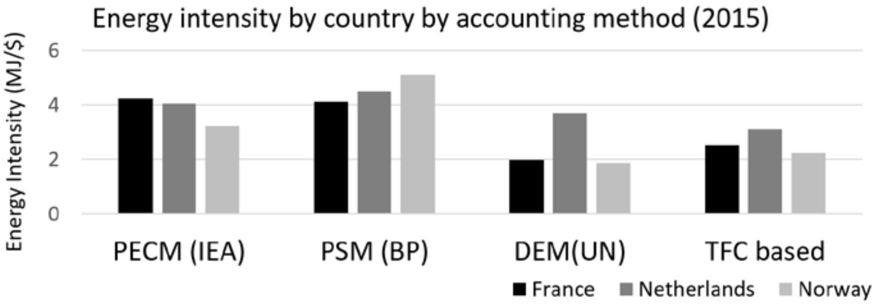


Figure 4.5 – Energy Intensity by selected country by accounting method in 2015. Data from [31, 241]

will require a diverse set of metrics. Based on the above considerations the following set of recommendations for the use of TPE, EE and EI can be made:

1. As a minimum, when TPE targets are set, data are supplied or scenarios are displayed, the energy accounting method should be explicitly given. Preferably, it should also highlight possible consequences of the used approach on the interpretation of the reader such that conclusions based on statistical artefacts are prevented.

2. Although climate related policy targets set with regards to energy metrics can make these policy targets more concrete, they should be subsidiary and serviceable to the target of lowering GHG emissions. Therefore, targets set relative to TPE, EE and EI should include an additional premise to prevent interference with GHG reduction.

3. Given the difficulties surrounding TPE, together with ongoing developments that decreases it significance and the shift of focus from resource availability to the impact of consumption, we would recommend, to focus on Total Final Consumption. TFC, being the energy as used (consumed) is free of definitional ambiguity: it is the sum of the Joules as consumed. Shifting from TPE to TFC would mean that the indicators energy efficiency and energy intensity would also be better expressed in terms of consumption. This would mean that energy efficiency would in practice be equal to energy service efficiency, i.e. the energy consumption needed to deliver a certain kind of service, see Equation 4.3. This can be expressed as passenger km / GJ for personal transport, tonne km / GJ for freight transport, heating and lighting requirement per GJ for the building sector etc. The same holds for Energy Intensity, which would be better expressed in TFC to prevent the mentioned problems with TPE, see Equation 4.4. Figure 4.5 shows the

effect of using a TFC in the calculation of EI in the three discussed cases.

$$EE = \frac{EnergyService}{TFC} \tag{4.3}$$

$$EI = \frac{TFC}{GDP} \tag{4.4}$$

The disadvantage of the use of TFC is of course that some information is lost as the efficiency of production of non-renewable energy carriers is neglected in this metric. However, now that the energy transition unfolds, focus has shifted from the availability of primary energy resources to the effect of consumption of these resources. Moreover, since the renewable-share of the energy mix is expected to increase as the energy transition unfolds, this problem, in comparison to the ambiguities surrounding TPE is expected to decrease.

4.3 The use of Electricity Generation Capacity

Next to primary energy and its related indicators, another important metric of which the meaning changes and becomes increasingly ambiguous with increasing shares of renewable resources, is electricity generation capacity (EGC). EGC figures are widely reported to show e.g. how much generation capacity a specific country has added or will be adding from a specific technology. In general, organisations report this metric to show the development of the electricity generation capacity mix, accompanied by headlines such as *renewables accounted for almost two-thirds of net new power capacity around the world in 2016* [242, 243] Moreover, India has framed one of its targets in these terms: "To achieve about 40 percent cumulative electric power installed capacity from non-fossil fuel based energy resources by 2030" [208].

Whereas TPE has become difficult to appreciate because the focus of stakeholders has changed from total resource availability to the impact of energy consumption, the interpretation of EGC has become difficult for a different reason. Whereas previously the total resource availability was of concern (i.e. oil, gas or coal reserves), now the momentary resource availability is of concern, i.e. solar radiation and wind. The intermittent character of these renewable resources make the availability of these resources on a second to second scale relevant. Capacity factors, the ratio of the average actually power production over the maximum power production, expresses this intermittent character of technologies (see Figure 4.6).

Previously the actual production of dispatchable thermal generation depended on the electricity demand. EGC values therefore where comparable as they

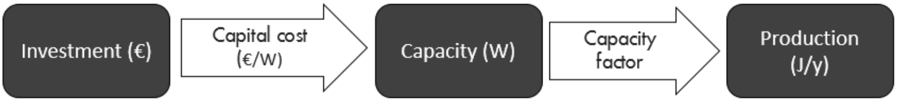
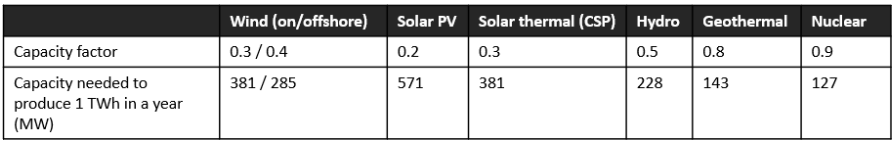


Figure 4.6 – Relationship between investments, capacity factors and actual production.

referred to their actual achievable maximum capacity. The production of renewable power generation however is predominantly depended on the availability of resources. This is illustrated with Table 4.2. It gives an overview of capacity factors reported by the IRENA [244] and EIA [245]. It shows that a similar sized electricity generator that is used for base-load electricity can have capacity factors of ca 90%, while solar PV panels have an average capacity factor of ca 20% (although very dependable on geographical location of the plant). Table 4.2 also shows how much capacity would need to be added to produce a similar amount of electricity around the year.

Since these capacity factor differ across (renewable) technologies, the metric EGC becomes technology dependent and its aggregate value becomes meaningless, as does comparison between technologies. Appreciation of progress on climate related policy targets is impossible from the reporting of bare EGC numbers. Moreover, targets set on (renewable) EGC, by all means do not guarantee to decrease the impact of the energy system on climate change; if electricity demand increases faster than the expected production from renewable EGC (multiplying EGC with the associated capacity factors per technology), emissions can de facto increase.

Table 4.2 – Average capacity factors of renewable generators in 2017, rounded to one decimal. Data from IRENA [244] and EIA [245]



	Wind (on/offshore)	Solar PV	Solar thermal (CSP)	Hydro	Geothermal	Nuclear
Capacity factor	0.3 / 0.4	0.2	0.3	0.5	0.8	0.9
Capacity needed to produce 1 TWh in a year (MW)	381 / 285	571	381	228	143	127

4.3.1 Recommendations on the use of EGC

If one wants to establish an appreciation of the renewable power industry or define targets in NDCs, newly added EGC does not give an un-ambiguous representation of the target or industry. Therefore, we would give the users of this metrics the following three recommendations:

1. Reporting EGC accompanied by the expected capacity factor would improvement the appreciation of the reported development as it would show how much product (electricity) actually would be expected to be produced.
2. Next to EGC the size of the involved investment would provide relevant information to assess the development of the industry (see Figure 4.6). As the world is moving from a world where the value of energy is embedded in the resource to a world where the technology is essentially the resource, additionally reporting on the associated investment gives a better representation of the system.
3. Targets set on (renewable) EGC should be avoided as policy interference is difficult to prevent. Targets set on the share of actual electricity production from renewable, zero-carbon resources using a similar production efficiency across these resources would already be an improvement.

In conclusion, appreciating EGC gives severe difficulties as referring to EGC in solitude gives a distorted view on the reality of the energy system. These difficulties can be overcome by simultaneously reporting other relevant and related metrics e.g. capacity factor, investment size.

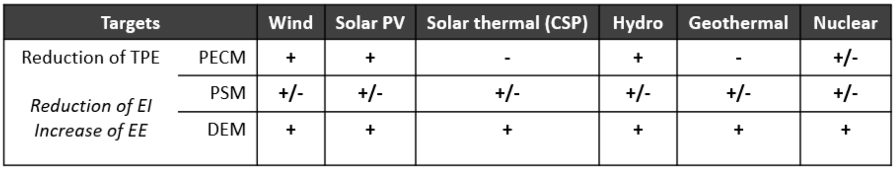
4.4 Reflection on findings and consequences for policy design

It has been shown that appreciation of TPE and its related indicators EE and EI as well as the metric EGC becomes increasingly difficult now that the energy transition progresses. Tables 4.3 and 4.4 show that various policy targets, generally used in NDCs, can potentially steer investments based on statistical artefacts.

Table 4.3 shows a qualitative assessment of the effect of policy targets set in terms of TPE (in the different accounting methods) on the attractiveness of a specific energy resources. The table indicates that although replacement of a fossil resource with one of the listed sources in reality reduces CO_2, in various superficial accounting realities they do not. Minuses indicate that a specific resource is less attractive than a fossil alternative when policy is steered on the mentioned targets.

Policy targets set in EGC give similar difficulties. Policy design aimed at increasing the share of renewable power capacity in reality is an in-effective policy tool to steer investment. Table 4.4 gives a qualitative assessment of the effect of a policy target combined with the deployment of a specific technology on the mitigation of climate change. Minus signs are given when the capacity factor of

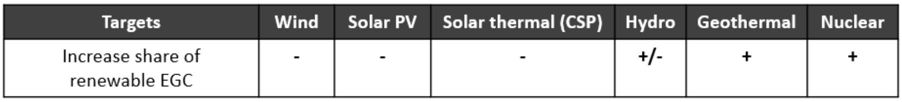
Table 4.3 – Qualitative assessment of the effect of policy targets set in TPE or related indicators (in the different accounting methods) on the attractiveness of a specific energy resource relative to the use of a fossil equivalent.



Targets		Wind	Solar PV	Solar thermal (CSP)	Hydro	Geothermal	Nuclear
Reduction of TPE	PECM	+	+	-	+	-	+/-
Reduction of EI *Increase of EE*	PSM	+/-	+/-	+/-	+/-	+/-	+/-
	DEM	+	+	+	+	+	+

EGC with a specific resource is lower than that of a fossil, thermal power station and plus signs vice versa. Table shows that with a given electricity demand, increasing the share of renewable capacity with, relative to fossil resources [246], low capacity factors, actually leads to an increased use of fossil resources.

Table 4.4 – Qualitative assessment of the effect of policy targets set in EGC on the reduction of climate change impact relative to the use of an fossil equivalent.



Targets	Wind	Solar PV	Solar thermal (CSP)	Hydro	Geothermal	Nuclear
Increase share of renewable EGC	-	-	-	+/-	+	+

In general it undesirable that energy related policy targets interfere with the overarching climate related policy targets. Moreover, it is undesirable that one zero-emission technology will be promoted over another zero-emission technology solely based on accounting artefacts.

Based on these considerations, and the recommendations stated in Section 4.2.3 and 4.3.1 we would argue that climate policy targets such as the National Determined Contributions (NDCs) submitted as part of the process initiated by the Conference of Parties in Paris 2016, should be set in terms of CO_2 to prevent policy interference. These targets could subsequently be supported by energy-related measures, which as we have argued are best expressed in terms of consumption (Total Final Consumption).

4.5 Conclusion

Now that climate policies focus more and more on the deployment of renewable, non-combustible energy sources (e.g. wind and solar radiation) the way these non-combustible energy sources are represented in energy data becomes increasingly important. Especially now that international climate negotiations are based on National Determined Contributions (NDCs), the appreciation and monitoring of progress on these targets needs transparent and consistently defined metrics.

However, as has been shown, key metrics often used in these NDCs, (Total Primary Energy and its related indicator Energy Efficiency and Energy Intensity as well as Electricity Generation Capacity) are becoming unrepresentative with large scale electrification and decarbonisation of the electricity system. Given the inconsistencies of the various accounting rules these metrics at best become confusing and at worst are derailing climate mitigation efforts.

In this paper it has been shown that these inconsistencies matter. Metrics influence outcomes of scientific research, political decisions and investment by private parties. Unfamiliarity of these inconsistencies on the part of policy makers or the general public can lead to adverse effects. It can potentially steer climate policy and investment decisions based on statistical artefacts, rather than a valid representation of the energy system.

Therefore, we argued, that both for policy development as well as for monitoring, a different set of energy metric is needed. As the overall objective of climate policy is to decrease greenhouse gas emissions, policy targets should be expressed in metrics that support this target.

Therefore, we recommend to have a clear overall target set in terms of emissions. For energy policy targets in support of these, we recommend to shift from Total Primary Energy to Total Final Consumption. Although not a panacea, we have argued that, as policy concern has shifted from total resource availability to the impact of resources, Total Final Consumption is a more relevant energy metric to track the development of the energy transition. With regards to renewable electricity we recommend focus on a broader set of metrics and not on EGC in solitude.

Our advice for energy modellers would be to be explicit about assumptions going into the energy scenarios. This holds especially on the definition of TPE as we have argued that a clear mentioning of this accounting issue, and its potential effect on the interpretation of these scenarios, would greatly improve understanding.

Building effective policy, making investment decisions and studying the energy transition, requires clear understanding of the building blocks of such analyses. This paper has given business decision makers, scientific researchers and policy developers essential background to appreciate these key energy metrics.