Title	Consumption-based approach to RES-E quantification: Insights from a Pan-European case study
Authors	Gaffney, Fiac;Deane, John Paul;Collins, Seán;Ó Gallachóir, Brian P.
Publication date	2017-11-05
Original Citation	Gaffney, F., Deane, J. P., Collins, S., and Ó Gallachóir, B. P. (2018) 'Consumption-based approach to RES-E quantification: Insights from a Pan-European case study', Energy Policy, 112, pp. 291-300. doi:10.1016/j.enpol.2017.10.024
Type of publication	Article (peer-reviewed)
Link to publisher's version	10.1016/j.enpol.2017.10.024
Rights	© 2017, Elsevier Ltd. All rights reserved. This manuscript version is made available under the CC-BY-NC-ND 4.0 license. - https://creativecommons.org/licenses/by-nc-nd/4.0/
Download date	2025-08-04 00:40:53
Item downloaded from	https://hdl.handle.net/10468/5300

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Title page

Consumption-based approach to RES-E quantification: Insights from a pan-European case study

F. Gaffney [ab*] J.P. Deane [ab] S. Collins [ab] B.P. Ó Gallachóir [ab]

[a] Energy Policy and Modelling Group, MaREI Centre, Environmental Research Institute, University College Cork, Ireland

[b] School of Engineering, University College Cork, Ireland

* Corresponding author at: Energy Policy and Modelling Group, MaREI Centre, Environmental Research Institute, University College Cork, Ireland

Email: fiac.gaffney@ucc.ie

*Revised Manuscript
Click here to view linked References

Abstract

The nexus between renewable electricity (RES-E) generation and interconnection is likely to play a large part in future de-carbonised power systems. This paper examines whether RES-E shares should be measured based on consumption rather than production with a European case study presented for the year 2030. The case study demonstrates the volume and scale of RES-E transfers and shows how countries have differing RES-E shares when comparing those derived based on the traditional production-based approach to the alternative. The proposed consumption-based approach accounts for RES-E being imported and exported on an hourly basis across 30 European countries and highlights concerns regarding uncoordinated support mechanisms, price distortions and cost inequality. These concerns are caused by cross-border subsidisation of electricity and this work proposes that an agency be appointed to administer regional RES-E affairs. This agency would accurately quantify RES-E shares and remunerate producers from the country that consumed their electricity instead of where it has been produced – policy would be enhanced by enabling more equitable and optimal electricity decarbonisation.

Highlights

- Consumption-based methodology to quantify RES-E is presented
- Consumption-based approach accounts for impact of RES-E imports & exports
- International agency could implement approach to address price distortions
- Policy is enhanced by enabling more equitable and optimal electricity decarbonisation

1. Introduction

Globally, power sector portfolios are undergoing a technology transformation with the ambition of achieving long-term carbon-neutrality. The Paris agreement of 2015, signed by 195 countries, is a significant driver of technological change as a concerted effort is needed to limit greenhouse gas emissions in order to keep global temperatures 'well below' 2°C above pre-industrial levels (European Commission, 2015). The European Union's (EU) Emissions Trading Scheme (ETS) as well as various climate and energy packages are policy instruments that promote the decarbonisation of the energy system through incentivising emissions reduction, increasing energy efficiency and increased deployment of renewables. Higher levels of variable renewable electricity (RES-E) can pose challenges for power system operation as they produce non-synchronous and non-dispatchable electricity (i.e. wind, solar, wave, tidal) (Schaber et al., 2012). These challenges can be mitigated to a certain extend by interconnection to neighbouring systems (Booz & Co. et al., 2013; Denny et al., 2010). Furthermore, as renewable generation grows, there is an increasing likelihood that RES-E may be exported to neighbouring countries during periods of excess power. While the authors are cognisant that '*an electron is an electron'* no matter how it is generated, it is also recognised that RES-E targets in many regions do, in fact, differentiate between electrons – by source.

EU Member States for example, must achieve renewable electricity targets based on "*the quantity of electricity produced in a Member State from renewable energy sources*" as a proportion of Gross Final Consumption (GFC),[1] as stated in Article 5(3) of the Renewable Energy Directive (2009/28/EC) (European Commission, 2009a). Applying a production-based approach is sensible in an isolated, closed system where electricity production must equal consumption; meaning all renewable electricity is consumed domestically. However, interconnector transfers and planned increases in capacity[2] are playing an increasingly important role in today's European power system, i.e. making it easier to share renewable

[1] The GFC of electricity is, for the purposes of RES-E calculations, defined as: "*Gross electricity production from all energy sources (actual production, no normalisation for hydro and wind), excluding the production of electricity in pumped storage units from water that has previously been pumped uphill; plus total imports of electricity; minus total exports of electricity.*" Eurostat, 2015. SHARES Tool Manual Version 2015.70124. Eurostat, European Commission.

[2] Interconnection capacity targets for Member States are 10% and 15% of installed electricity production capacity by 2020 and 2030 respectively. European Commission, 2017. Renewables: Europe on track to reach its 20% target by 2020, European Commission - Fact Sheet.

electricity surpluses and improving the operational control of a system. Equally a patchwork of varying national support schemes for renewable generation has led to situations where renewables are built where support is the strongest, rather than where the most cost-effective. Consequently, transfers of renewable electricity across interconnectors can present situations where the costs of renewable electricity are subsidised in one country and consumed in another. This therefore begs the question whether a consumption-based accounting approach to quantifying renewable electricity, which considers these transfers, should be used?

The Renewable Energy Directive already acknowledges that it is appropriate to facilitate the consumption of energy in one Member State which has been produced from renewable sources in another in order to meet defined targets in a cost-efficient manner. The directive proposes flexibility measures in the form of statistical transfer and joint projects between Member States to facilitate this. However, Member States have so far not engaged in these schemes with just two exceptions: Sweden and Norway (non-EU Member State); and Denmark and Germany (International Energy Agency, 2016b). Uncoordinated financial support schemes have the potential to cause price distortions between neighbouring countries which can lead to electricity transfers that do not provide societal gain and potentially cause cost inequalities as RES-E supported in one country is consumed in another, raising questions around 'who pays the difference between the market price and support scheme strike price?' Viewing renewable generation from a consumption-based standpoint delivers a different perspective on the intricacies involved in electricity generation and transmission. Identifying the movement of RES-E between countries opens 'Pandora's box' in terms of accounting for RES-E shares, costs inequalities associated with transferred RES-E and potential price distortions but it also sheds light on whether the current production-based approach is 'fit for purpose' in a future de-carbonised electricity sector.

In this paper, a consumption-based approach for quantifying a country's RES-E share is proposed and implications for renewable support schemes are discussed. The methodology is based on the concept of measuring the RES-E that is actually consumed within a country's boundary rather than what is produced. Accounting for interconnector inflows and outflows is a fundamental part of the methodology that provides the key difference between this and a traditional 'production-based' approach. The proposed consumption-based approach is demonstrated using the European internal market for electricity (hereafter; EU Target Model) as a case study for a single year. Note that under the Renewable Energy Directive for example, consumption-based measurement of renewables is used for the transport and heating & cooling sectors.

Using PLEXOS® Integrated Energy Model, a European electricity model for 2030 is created based on the recent European Commission's Reference Scenario (Capros et al., 2016). Once simulated, the results are post-processed to determine the country[3] where RES-E is produced and more importantly, where it is consumed, on an hourly basis. In doing so, issues associated with mass RES-E transfer across Europe are captured, such as uncoordinated support schemes, price distortions and cross-border subsidisation. These insights allow an in-depth discussion on the challenges and the institutional structures that need to be addressed to achieve a low carbon power system.

While many publications concentrate on topics such as the production-based versus consumption-based quantification question (Fan et al., 2016; Ji et al., 2016; Larsen and Hertwich, 2009; Peters, 2008; Shao et al., 2016; Simas et al., 2017; Wiedmann, 2009), the facilitation of RES-E in power systems (Cleary et al., 2016; Collins et al., 2017; Daly et al., 2015; Deane et al., 2015; EirGrid & SONI, 2010, 2011; Fraunhofer IWES, 2015; Gaffney et al., 2017b; Henriot et al., 2013; McGarrigle et al., 2013) and/or the importance of border trade (Bahar and Sauvage, 2013; Booz & Co. et al., 2013; Denny et al., 2010; EirGrid & SONI, 2010; EURELECTRIC, 2016; Fraunhofer IWES, 2015; International Energy Agency, 2016a) regarding their respective place in a future decarbonised electricity system, few publications focus on the quantification requirements when both RES-E integration and cross border trade are taken together. Ji et al. (2016) highlight a concern surrounding electricity traded between power systems and the characteristics associated with the transfer. Focusing on the greenhouse gas emissions aspect of traded electricity, Ji et al. (2016) outline a high-level proposal to account for both direct and in-direct emissions that widens the boundary under consideration when addressing the concern.

Building upon Ji et al.'s concept of 'broadening the boundary under consideration,' we present a test case that highlights: 1) the short-comings of a production-based approach in interconnected systems with high levels of renewables; 2) challenges and potential solutions for the European internal market in 2030; and 3) concerns over pecuniary externalities caused by cross-border subsidisation and uncoordinated support schemes which can lead to issues

[3] "Country" is preferred over "Member State" as not all countries in the model are part of the European Union, i.e. Norway and Switzerland.

surrounding effects on investment signals and long-term security of electricity supply problems.

The paper is structured as follows. Section 2 outlines the methodological approach and assumptions used during the analytical phase of the paper. Section 3 overviews the main results from the analysis, while Section 4 discusses various potential impacts associated with the proposal along with considerations related to its implementation. Section 5 concludes the paper with some final remarks.

In an effort to promote transparency, the PLEXOS® model and the excel tool used to calculate renewable electricity flows, along with all associated data have been made freely available online for academic research at: https://www.dropbox.com/sh/m6pik1iql3ddpuj/AABYdHHk4_43WpGoSFNx329Aa?dl=0

2. Methodology

The methodology applied combines a soft-linking approach between energy system and power system models, as described by Deane et al. (2012), with a post-processing phase to ascertain the volume of RES-E that is both produced and consumed in each country included in the analysis. First, the European Commission's Reference Scenario is soft-linked to a power system model comprising of 30 European countries (EU-28 Member States,[4] Norway and Switzerland) focusing on the year 2030. Post-processing is carried out on an hourly basis, in line with the EU Target Model day-ahead market scheduling algorithm known as EUPHEMIA.[5] This analytical phase will address the phenomenon known as 'wheeling', where electricity may be traded through one country to access another, based on wholesale market price differentials. Through analysis of the data it is possible to separate the share of interconnector flows subject to 'wheeling' compared to that derived directly from the country in question.

[4] At the time of writing, the United Kingdom remains a constituent of the European Union.

[5] Acronym: '*EU Pan-European Hybrid Electricity Market Integration Model*.' For more information on the EUPHEMIA algorithm, see the developer N-SIDE, EUPHEMIA, Brussels. or operator Price Coupling of Regions, 2016. EUPHEMIA: Description and Functioning, in: PCR (Ed.), EUPHEMIA Stakeholder Forum. EPEX Spot, Brussels.

2.1. Power system simulation

PLEXOS® Integrated Energy Model (PLEXOS®) is a power system modelling platform used for power and gas market modelling (Drayton et al., 2004). The software is a unit commitment and economic dispatch modelling tool that optimises at least cost the operation of the electricity system over the simulation period at high technical and temporal resolution whilst respecting operational constraints. Version 7.4 (R02) of PLEXOS® was operated on a Dell Inspiron CN55905 laptop with a 6th Generation Intel® Core i7-6500U Processor. The MOSEK solver was used to simulate the model with Rounded Relaxation unit commitment applying a 0.01% relative gap and 6-hour look-ahead. Using hourly dispatch, in line with the EU Target Model day-ahead market scheduling platform, 365 days were simulated to replicate 2030, taking 1.5 hours to complete.

2.1.1. Scenario description

The installed power generation capacities for the EU-28 Member States were outlined in the European Commission's Reference Scenario by generation class, for example; Hydro, Oil, Gas, Solids, Biomass/Waste, et cetera. The portfolios were disaggregated into individual power plant types by fuel class and assigned standard technical characteristics as shown in Table 1 and Table 2 an approach used previously by Deane et al. (2015). Assumptions based on ENTSO-E (2015) Ten Year Network Development Plan – Vision 1[6] publication were used to represent the Swiss and Norwegian power systems.

The model is simulated as a closed loop comprising of 30 European countries and 58 interconnectors and overall regional generation must meet regional load in each hour simulated. Therefore, when all hourly interconnector flows (exports and imports) are summed, the result (net of interconnector transfer losses) must be zero, as shown in Eq. (1).

$$0 = \sum_{i=1}^{58}(IC_i) \qquad (1)$$

where *i* represents interconnectors and *IC* is the flow of electricity on an interconnector. *IC* flow is positive for exports and negative for imports.

[INSERT Table 1]

[INSERT Table 2]

[6] Vision 1 was chosen over the other scenarios represented as it was the most conservative 2030 option and, therefore, most closely aligned with the European Commission's Reference Scenario.

Demand profiles: Hourly resolution demand curves were attained from historic ENTSO-E data (ENTSO-E, 2012) and linearly scaled to the overall demand estimates outlined in the European Commission's Reference Scenario.

Wind, solar and hydro profiles: Hourly generation profiles for wind power were sourced from Gonzalez-Aparicio et al. (2016). Solar profiles were created from NREL's PVWatts® calculator which estimated the solar radiance from assumptions around system location and basic system design parameters for each country (Dobos, 2013). Hydro profiles are decomposed from monthly generation constraints provided by ENTSO-E (2012) to weekly and hourly profiles in the optimisation algorithm function in PLEXOS®.

Pumped hydro energy storage is not simulated in this model for the reason being that it increases simulation time significantly but more importantly because under Article 5(3) of the Renewable Energy Directive *"renewable energy sources shall be calculated as the quantity of electricity produced in a Member State from renewable energy sources, excluding the production of electricity in pumped storage units from water that has previously been pumped uphill."* (European Commission, 2009a, p.29).

Interconnection: The interconnection capacities between countries represented in the model are based on projections from the ENTSO-E (2015) *'Ten Year Network Development Plan 2016'* publication, see Figure 1.[7] Interconnection is limited to net transfers between countries and excludes interregional transfers in line with the EU day-ahead market schedule dispatch clearing algorithm, EUPHEMIA.

[INSERT Figure 1]

2.2. Post-processing

Post-processing is required to identify the RES-E flow across Europe's interconnectors for each hour of a given year. Due to the complexity associated with tracing wheeled exports to their source(s), this approach employs an iterative process to continually improve calculation accuracy until all RES-E transfer is accounted for. The foundation of this approach lies with

[7] Malta is the only electrically isolated country represented in the model.

the identification of the true source(s) of wheeled exports in each hour. Once known, the exported electricity is checked for any RES-E content. While in most cases no RES-E exist, when it does however, it is possible to trace the energy to its point of consumption purely based on the economic dispatch of generation portfolios and the merit-order approach (Sáenz de Miera et al., 2008; Sensfuß et al., 2008).

This approach functions on the assumption that all country-specific electricity markets within the model employ an economic dispatch approach, therefore RES-E is consumed locally to meet domestic load before any renewable exports can occur. This is supported by the requirement under Article 16 of Renewable Energy Directive for transmission system operators to comply with their duty to minimise curtailment of renewable electricity and based on the knowledge that a high share of EU RES-E generation receive power purchase agreements through government backed support schemes, as demonstrated by RES Legal (2017). Therefore RES-E can bid in low, zero or negative bid prices to the energy market to reduce dispatch exposure.[8] Furthermore, when RES-E flow has been identified as travelling between countries the same principal is used in the importing country in terms of economic dispatch. In other words, RES-E is only exported if the combined domestic RES-E and imported RES-E (if applicable) exceeds domestic load.

2.2.1. Components of interconnector flow

In this methodological approach, electricity transferred via interconnection is considered a combination of two components. The electricity is either a direct product of the country where the interconnector originates or an indirect product which is derived from another location and passes through one country to another, also referred to as 'wheeling electricity'. Henceforth the first is referred to as "Domestic Exports," the second "Wheeled Exports." Domestic Exports (DE) occur when domestic generation exceeds domestic load, causing an export of electricity directly associated with the country in question. Wheeled Exports (WE) are equal to interconnector flow net of Domestic Exports, see Eq. (2).

$$IC_i = \sum_{i=1}^{58} (DE_i + WE_i) \qquad (2)$$

where,

[8] RES-E generation has the advantage of priority dispatch under the Renewable Energy Directive (2009/28/EC). This may not be in the case in 2030 as outlined in the draft directive on the Internal Electricity Market. European Commission, 2016b. Proposal for a Regulation of the European Parliament and of the Council on the internal market for electricity, COM(2016) 861 final - 2016/0379 (COD). European Commission, Brussels.

- DE = Domestic Generation – Domestic Load
- WE = Interconnector Flow – Domestic Exports (if Domestic Exports >0)

else,

- WE = Interconnector Flow

where *i* represents interconnectors.

2.2.2. Calculating the RES-E share of interconnector flows

To measure the RES-E share of Wheeled Exports across an interconnector, the true source of the electricity must first be determined by tracing interconnection flows back to their origin. In doing so, what is actually identified as the source of Wheeled Exports is the Domestic Exports of a country that is not importing electricity. Therefore, to identify the source(s) of wheeled electricity in a given hour a country must export electricity and not import, as shown in Eq. (3). The RES-E share of electricity transfer is then assessed and if applicable, quantified using Eq. (4). Eq. (4) states that RES-E generation *must* first exceed domestic load for any renewable export to occur. If RES-E export occurs, it is demonstrated as a share of domestic exports as shown in Eq. (4). Finally, the results are tabulated to determine the RES-E volume *imported* into each country in a given hour, thereby concluding **Step 1** in what is an iterative process to ascertain the RES-E share of all interconnector flows.

$$True = \sum_{j=1}^{n}(Exp_j) > 0 \;\&\; \sum_{j=1}^{n}(Imp_j) = 0 \qquad (3)$$

$$RES\_\%_j = \sum_{j=1}^{30}\left(\frac{RES\ Gen_j - Dom\ Load_j}{Exp_j}\right) \qquad (4)$$

where,

- RES-E Generation - Domestic Load > 0

where *j* represents the country and *n* is the maximum number of interconnections. *Exp* and *Imp* represents electricity exports and imports respectively from a country. *RES_%* is the renewable share of exports.

Figure 2 and the following explanation describes how each step in the post-processing phase relates to the next in terms of accounting for RES-E transfer across interconnector capacity. In **Step 1** the figure shows Country A as the only country to successfully meet the requirements outlined in Eq. (3) and Eq. (4). In other words, Country A is the source of wheeled RES-E exports. As such, interconnector flow between countries ‘A – B’ and ‘A – S’ are represented by *green* unbroken lines to signify RES-E flow in a given hour. The main objective of **Step 1** is to identify the sources of wheeled exports in each hour and assess if renewable energy is present. The following steps use this information as a foundation to trace the RES-E flows to their final location through multiple iterations.

[INSERT Figure 2]

Step 2 sums the imported RES-E, as identified in the previous step, and the domestic RES-E to determine if renewable exports occur in a given hour. This calculation must abide by the condition that RES-E generation fulfils domestic load before renewable exports are possible. From Step 2, the information is again tabulated to identify the RES-E volume imported into each country in a given hour.

To best illustrate Step 2 using Figure 2, the focus is on the transfer between countries ‘B – C’ and ‘S – B’. The figure shows the interconnection between ‘B – C’ in this step as a red broken line to indicate that no RES-E flow, therefore the combination of imported and domestic RES-E does not exceed domestic load in Country B. However, the RES-E flow between ‘B – C’ has not yet fully accounted for all RES-E flow up-stream. In Step 1, the interconnector from ‘S – B’ had no RES-E flow as imports from Country A were not yet accounted for in Country S. In Step 2, this RES-E flow is accounted for and the interconnection between S – B is green – meaning the combination of imported and domestic RES-E exceeds domestic load and RES-E is exported. However, the interconnector ‘B – C’ has not yet taken account of this additional RES-E flow wheeled through Country S. This imprecision is corrected in Step 3 when the RES-E flow becomes fully accounted for across the interconnection ‘B – C’. As a result, the interconnection changes to a green unbroken line which indicates RES-E flow - meaning that the combination of imported and domestic RES-E exceeds domestic load in Country B. For this reason, this methodological approach employs an iterative approach to account for the numerous interconnection flows that occur in a meshed grid, such as the European electricity system represented in this paper by 58 interconnectors and 30 countries.

Step 3-6: Steps 3-6 are identical to Step 2, with each using the table from the previous step to identify the RES-E volume of imported electricity, i.e. increasing accuracy with each step. This methodology uses as many steps as necessary to account for all RES-E flows. While comparing Step 5 to Step 6, the results for all 58 interconnectors across Europe over the year were identical, therefore Step 5 was the final iteration.[9] These values account for renewable electricity flows all the way back to their source and provide an insight into the locations where RES-E is consumed on an hourly basis for the year 2030.

3. Results

This section presents results and analysis from the applied methodology and simulated 2030 European model.

3.1. Wholesale electricity prices

Figure 3 demonstrates wholesale price differentials with 26 countries inside ±10% of the €73.21 per MWh average. Low price differentials are observed due to the increased level of interconnection capacity expected in 2030. The Czech Republic has the highest wholesale price of any electrically interconnected country simulated, it also experiences the highest level of interconnector congestion (55%) over the year. This congestion is caused by physical transmission capacity constraints and directly contributes to price formation as lower cost electricity from surrounding countries cannot be imported at a sufficient rate to further suppress the marginal price.

[INSERT Figure 3]

3.2. RES-E interconnector flow

The method ology outlined in Subsection 2.2 is applied to identify and also quantify the RES-E contribution of electricity transfer between countries on a high temporal resolution. Figure 4, Figure 5 and Figure 6 show three insights to the findings from the post-processing phase. The figures outline the overall electricity flow and renewable electricity flow between countries along with the renewable share of the transferred electricity on an annualised basis.

[9] The number of steps may change depending on a number of variables, such as installed renewable generation capacity, interconnection capacities, domestic load, generation and load profiles, et cetera.

[INSERT Figure 4]

[INSERT Figure 5]

[INSERT Figure 6]

Figure 4, Figure 5 and Figure 6 highlight the unequal electricity transfer between a selection of countries over a year. The figures also demonstrate the difference in RES-E share that is transferred over the same period. However, it should be reiterated that both observations are contingent on assumptions surrounding generation portfolios and profiles used, demand curves, fuel costs, taxes, et cetera. Figure 4 shows Portugal and Spain transferring a similar amount of total electricity back and forth over the year, yet 66% of exported electricity originating in Portugal is from renewable sources while only 2% of electricity returned is considered renewable. Similarly, France exports high volumes of electricity to Spain but with no RES-E share, which is directly associated with its generation portfolio, i.e. high share of nuclear power. This can also be seen in Figure 5 where France is a net exporter to Germany but, again, with no RES-E share. Figure 5 further highlights the issue regarding RES-E share of imports-exports when analysing the interconnections between Germany-Denmark and Germany-Poland where large differences between RES-E contributions are identified. Figure 6 is perhaps the most striking example to show the significance, where hydro based Norwegian power is exported to the Denmark and UK at 99% and 100% RES-E over the year respectively. While Norway does not import significant quantities of electricity in the simulation, the volume that is imported has a much lower RES-E content. Table 3 demonstrates the net RES-E share transferred on each interconnector. Remaining cognisant of the conservative assumptions surrounding scenario selection, the analysis carried out as part of this paper estimates that 60 TWh of renewable electricity is transferred across European interconnectors in 2030 or 19% of total cross-border flow.

[INSERT Table 3]

3.3. Country-specific renewable electricity shares

Viewing renewable electricity in this alternative light opens ‘Pandora’s box’ in terms of accounting for the renewable electricity shares of each country. Identifying where renewable electricity is produced, transferred to and finally, where it is consumed in high temporal resolution is an accurate means of assessing the share of the electricity sourced from renewable sources that is *actually* consumed within state. Figure 7 compares RES-E shares of individual countries applying the current approach long used by the European Commission (RES-E production) to the alternative approach outlined in this paper that accounts for renewable electricity transfer across interconnectors (RES-E consumption).

[INSERT Figure 7]

Using the approach outlined in this paper, Figure 7 shows a higher number of countries with a different level of renewable electricity than what would otherwise be reported using the current production-based approach. In reality when wind generation is high in the Nordics and hydro-power capacity in Norway is generating low-cost electricity, excess generation is exported out of the Nordic region. While this electricity may be used elsewhere, it is still from a renewable energy source. The same applies when solar capacity in the more southern, warmer parts of Europe is producing high levels of power and this is transferred to load centres across the wider region, and so on. Applying the current approach used by the European Commission, while a simpler approach, does not account for this transfer.[10] For example, Figure 7 demonstrates that, when taken on an annualised basis, Norway has excess renewable electricity which is transferred to surrounding countries to meet their demand (if the correct price signals are in place.)[11] The traditional approach to quantifying RES-E does not capture this transfer or where RES-E is consumed and therefore could be seen as a poorer approach in calculating RES-E for adjoining countries. Denmark and Sweden are examples that show the inability of the traditional approach to account for the level of renewable

[10] The authors recognise that ‘Statistical Transfers’ are allowed under the Renewable Energy Directive (2009/28/EC), however this option is yet to be availed of by any Member State, at time of writing.

[11] This assumption is supported by evidence available from Eurostat, 2016. European Statistics. showing Norway producing 138 TWh of RES-E in 2015 to meet a GFC demand of 129 TWh.

energy *actually* consumed within state – which in both cases is higher than otherwise would be reported, as shown in Figure 7.

For simplicity, measuring RES-E production is an easier option. However, as electricity markets across Europe become more intrinsically linked and transition toward a complete EU-wide internal market, the current approach may no longer be the correct strategy to capture where RES-E is consumed and importantly where it is paid for. In Section 4 the case study results demonstrated thus far are expanded upon to discuss issues around cross-border subsidisation, price distortion and cost inequality.

4. Discussion

Section 3 results demonstrate the difference between a consumption and production-based approach to quantifying RES-E in Europe. This section examines a number of considerations and impacts associated with the findings and discusses the possible consequences.

4.1. What does a consumption-based approach offer?

A consumption-based approach improves clarity, accuracy and awareness of where RES-E is produced and it is consumed. The clarity of knowing where electricity is generated, how interconnector flows are determined and the effects of generation portfolios in neighbouring countries. Improved accuracy through the accounting of imported renewable electricity generated outside of state boundaries yet consumed within, and the awareness of potential issues that can arise when the volume and scale of RES-E transfers across the region escalate. A consumption-based approach also sheds light on issues of price distortion (caused by uncoordinated support schemes) and cross-border subsidisation (creating cost inequality).

4.2. Who pays the 'true' cost of transferred renewable electricity?

The EU Target Model is designed to promote the free flow of electricity throughout Europe unaffected by network constraints or price distortions to achieve a price convergence across the region. While Figure 3 shows the effects of this framework in terms of a relatively shallow price range, Figure 4, Figure 5 and Figure 6 reveal a different perspective on unconstrained electricity flow regarding renewable electricity transfer. Acknowledging that significant volumes of RES-E capacity across Europe are supported outside of the energy market through support mechanisms, and yet interconnector flows are based on wholesale energy market prices, this creates a paradox. As more RES-E capacity is installed, wholesale electricity prices reduce further due to the merit order effect, becoming more attractive to export at a price that is *not* truly reflective of the cost to generate the power being exported. Thereby leaving the country where the renewable electricity is produced to meet the stipulations of the support schemes in place, i.e. remunerate the RES-E capacity to the agreed terms and conditions while the energy is consumed outside of state borders.

For instance, the simulation shows that the interconnection capacity from Denmark to Sweden exports (imports) approximately 1.8 (1.6) TWh over the year. When Denmark exports to Sweden the electricity is 35% RES-E compared to 0.4% when flows reverse, as can be seen from Table 3. Coupled with the examples shown in Figure 4, Figure 5 and Figure 6, this demonstrates that countries such as Denmark, Portugal, Norway and Germany for example are exposed to cost inequalities if 1) electricity is traded on interconnectors using its wholesale price (which it is and will continue to do so in line with the EU Target Model) and 2) RES-E capacity is supported outside of the energy market (which is currently the case in most European countries). This longstanding concern around price distortion effects caused by pecuniary externalities is a well published topic, see (Buchan and Keay, 2016; Couture and Gagnon, 2010; Fouquet and Johansson, 2008; Glachant and Ruester, 2014; Gore et al., 2016; International Energy Agency, 2016a; Joskow, 2008; Lehmann and Gawel, 2013; Meyer and Gore, 2015; Roques, 2008). Nevertheless, with large volumes of RES-E capacity required to achieve the future goal of a decarbonised power sector, this challenge may be amplified and become a more widespread problem noting that this paper demonstrates a conservative view of what may actually unfold in 2030 (Capros et al., 2016).

Quantifying the financial implications for countries net-exporting RES-E is a challenging task as there has been little coordination between Member States when setting up RES-E support schemes across Europe over the years.[12] Neighbouring countries may endure dissimilar levels of price distortion due to the differing support structures, remuneration levels and/or contract lengths. Bearing in mind the current Member State specific RES-E targets for 2020, in simple terms this means if a country could not achieve the necessary uptake in RES-E capacity to meet national targets, the remuneration offered or scheme framework may be altered to increase its attractiveness through higher remuneration, longer

[12] While it must be recognised that the European Commission has used its “autonomous control power” regarding the policing of national state aids to shape support schemes in some way, as alluded to by Buchan and Keay (2016) and also having recently introduced a working document on guidance for the design of renewable support schemes European Commission, 2013. Guidance for the design of renewable support schemes - Commission staff working document. SWD(2013) 439 final. European Commission, Brussels., it is recognised that support sharing and full coordination has not yet been achieved to date.

contracts, or less risk-exposure. Ireland for example, changed its RES-E support in 2007 from a competitive bidding process to a centrally administered price setting scheme to increase profitability for RES-E generation capacity. According to Global Wind Energy Council & International Renewable Energy Agency (2013), many projects awarded financial support through the competitive bidding process in Ireland had not been built due to "*low bidding prices and lack of profitability"* (p.100).[13] In a similar vein to price distortions stemming from uncoordinated capacity mechanisms as discussed by Gaffney et al. (2017b); Glachant and Ruester (2014); Gore et al. (2016); Meyer and Gore (2015), uncoordinated RES-E support schemes may be viewed in the same light during the transition to a future regional market based on undistorted price signals. However, equally as important is the need to implement a framework for remunerating renewable electricity transferred across boundaries that improves cost equality – paying the 'true' cost rather than market price.

4.2.1. How to address price distortion

Viewing these concerns in the correct context is essential; meaning that the issue is borne out of a requirement for cross-boundary interactions, therefore the solution must also be viewed in the same geographical context. Introducing a coordinated approach to RES-E support schemes through a European agency could provide the solidarity needed for cost equality to thrive, and thereby maximising societal welfare for all European electricity consumers. An agency appointed to administer the renewable electricity affairs of the region that takes cognisance of individual economic, societal, technical and environmental conditions to create a level playing field, free of price distortion created by differing support structures. This may not be an excessively unrealistic proposal, instead it could be recognised as a new, or an expansion of an existing, department within the Agency for the Cooperation of Energy Regulators (ACER) for example. An agency which was created through the EU Third Energy Legislative Package (2009/72/EC) to ensure the smooth functioning of the internal energy market (European Commission, 2009b).[14]

[13] For more information on the development of wind power in Ireland and the entire Irish electricity system between 1916-2015, see Gaffney, F., Deane, J., Gallachóir, B.Ó., 2017a. A 100 year review of electricity policy in Ireland (1916–2015). Energy Policy 105, 67-79.

[14] This may be a timely suggestion as there is currently a proposal to strengthen ACER's powers and responsibilities included in the draft directive on the Internal Electricity Market European Commission, 2016b. Proposal for a Regulation of the European Parliament and of the Council on the internal market for electricity, COM(2016) 861 final - 2016/0379 (COD). European Commission, Brussels.

The chosen agency could also be responsible for accurately quantifying renewable electricity shares and remunerating producers from the country that consumed their electricity instead of where it has been produced – effectively socialising the cost of renewable electricity across state boundaries to improve cost equality during Europe's transition to a decarbonised system. This approach could be seen as a reform or even an evolution of the 'statistical transfers' permitted between Member States in Article 6 of the Renewable Energy Directive and Article 8 of the latest Renewable Energy Directive draft (European Commission, 2016a).

Increasing the accuracy of cost distributions associated with the consumption of renewable electricity may also provide secondary gains. Aside from reducing the level of revenue required to remunerate RES-E generation in an exporting country, this approach may lower the economic barriers surrounding the cost to consumers of developing higher levels of RES-E capacity. If, for example, a country has the correct topography and climate for hydro-powered generation, then the cost as well as the benefit of this renewable energy source can be shared with neighbouring nations. This may encourage further development in countries rich in potential renewable assets such as geothermal, solar, biomass, biogas, wave, tidal and wind energy by lowering the economic barriers which often add weight to institutional and organisational barriers as shown in publications by Byrnes et al. (2013); Foxon et al. (2005); Hvelplund et al. (2017); Lund et al. (2014); Lund and Quinlan (2014); Painuly (2001); Reddy and Painuly (2004); Scarpa and Willis (2010); Verbruggen et al. (2010).

4.2.2. Is there appetite for change?

Buchan and Keay (2016) highlight that the European Commission *"has twice tried, and twice failed, to persuade EU governments to adopt a harmonised EU-wide subsidy system."* (p.7). Therefore, an appetite appears to exist at EU level. Furthermore, Article 5 of the latest Renewable Energy Directive draft the European Commission includes plans to open access for RES-E support schemes to installations located in other Member States (European Commission, 2016a). However, legal conflicts such as the *PreussenElekra* case of 2001,[15] or more recently the *Ålands Vindkraft* case in 2014,[16] highlight the individual nature of EU Member States and the 'parochial' thinking that exists regarding environmental targets – albeit the very nature of individual targets encourages this behaviour.

[15] For more information, see: http://curia.europa.eu/juris/liste.jsf?language=en&num=C-379/98

[16] For more information, see: http://curia.europa.eu/juris/liste.jsf?num=C-573/12

The issue, is perhaps best epitomised by the Ålands Vindkraft case, where a windfarm situated in the Åland archipelago of Finland applied for a Swedish RES-E support scheme as it was directly connected to the Swedish system but not that of Finland. The application was rejected on the grounds that it was unfair for Swedish consumers to remunerate a wind farm contributing to Finland's RES target. Once this occurred, the boundaries of environmental protection were clearly drawn by Sweden, even in the face of breaching European energy market law surrounding the free movement of goods, i.e. electricity. While the European Court of Justice required justification from Sweden regarding the case, the ruling was in Sweden's favour as the argument was successfully made that the Renewable Energy Directive *does* permit the trans-boundary RES-E support schemes but *does not* require it (European Commission, 2009a). Therefore, Sweden were found to have acted within the boundaries of EU law.

Despite the European Court of Justice ruling, Durand and Keay (2014) believe that the Ålands Vindkraft case raises more questions than it answers regarding the relationship between environmental protection (and individual Member State targets) and its place within the European energy market law. Durand and Keay (2014) highlight that other Member States have cited the Ålands Vindkraft case as a justification for discriminatory practices. Germany for example, cited the case while attempting to introduce a surcharge on imported electricity through a new renewable energy law that would be used to finance domestic RES-E producers.[17]

While it is the opinion of Buchan and Keay (2016) that cross-border subsidy sharing may be a bridge too far at the time of publication, it must be seen as progressive that Norway and Sweden introduced a joint support scheme that includes an international agreement between the countries to recognised 'green energy' produced in another jurisdiction,[18] or that the German-Danish cross-border solar photovoltaic electricity auction was launched in 2016 (International Energy Agency, 2016b), or indeed, when the European Commission included plans supporting (and requiring) subsidy sharing in Article 5 of the latest Renewable Energy Directive draft (European Commission, 2016a). Remaining cognisant that the 'green energy contributions' conversation regarding joint, cross-border schemes will be 'null and void'

[17] For more information, see: http://www.reuters.com/article/eu-energy-idUSL6N0PE24C20140703 and http://curia.europa.eu/juris/liste.jsf?num=T-47/15

[18] The amount of 'green energy' contributed toward national RES targets would depend on the level of investment in the joint project.

post-2020 once national RES targets are relinquished for 2030, issues surrounding cross-border subsidisation of RES-E on a supranational scale will remain, and potentially increase due to heightened levels of both RES-E generation and installed interconnection capacity.

4.3. Considerations associated with a consumption-based alternative approach

Complexity, complexity, complexity. This proposal ensures much of it. Calculating the locations where renewable electricity is generated, how much is transferred, where it actually consumed, et cetera, is all involved work. Nevertheless, the alternative is to continue to use a methodology which may not be fit for purpose. Increasing the installed capacity of different renewable energies both in Europe and globally adds to the already multifaceted world of the electricity sector. As the penetration of renewable energies increase, as does the need for interconnection, support mechanisms, along with issues surrounding the 'missing money' problem, price distortions, and many more. While this paper does not provide the solutions to all these issues, it may be seen in a similar light to that published by Ji et al. (2016) as a 'thought-provoker', one that tries to unearth a different way of thinking about the future electricity sector.

Further research is necessary in numerous areas to add layers to this proposal. For instance; the identification of regulatory and institutional barriers is essential for any movement towards a new approach for calculating RES-E shares and establishing a framework around the cost inequality issue, identifying how to best approach this redistribution of costs are two important areas of research.

5. Conclusion

This paper proposes an alternative approach for quantifying the RES-E share of individual countries based on the volume consumed rather than produced to address potential inadequacies associated with the modern-day approach. As global power sector portfolios are undergoing a technology transformation to achieve carbon-neutrality over the long-term, renewable generation is fundamental to the cause along with high levels of interconnection to help facilitate the transition and remain as part of the enduring solution.

While increased interconnection capacity adds to the operational aspect of system control as non-synchronous RES-E can be safely and securely managed without curtailment being the first option, it also exacerbates an underlying issue with price distortions stemming from out-of-market financial support schemes that can decrease wholesale market prices. A paradox exists: as renewable generation (receiving out-of-market support) increases, wholesale electricity prices decrease, becoming more attractive to export at a price that is *not* truly reflective of the cost to generate that power. Consequently, this price distortion creates a cost inequality as consumers are left to remunerate the renewable electricity producer while the energy is consumed out of state. Using the EU Target Model as a case study, this paper provides an awareness to the potential volume and scale of the issue in a sector aiming for long-term de-carbonisation. The paper shows that even in a conservative 2030 scenario that significant volumes of renewable electricity is likely to be transferred on annual basis. This approach should not be considered exclusive for Europe, instead it could be thought of as being applicable to any region with a similar nexus between renewable electricity generation and interconnection to surrounding systems.

This paper suggests that tackling price distortions associated with renewable generation support mechanisms may be best approached from a supranational perspective. An agency, such as ACER within the EU, could provide the solidarity needed for cost equality to thrive, thereby maximising societal welfare for all electricity consumers in the region. Appointed to administer the renewable electricity affairs of a region, this agency should take cognisance of individual economic, societal, technical and environmental conditions to create a level playing field, free of price distortion created by differing support structures. An agency responsible for accurately quantifying renewable electricity shares and remunerating producers from the country that consumed their electricity instead of where it has been produced – effectively socialising the cost of renewable electricity across state boundaries to improve cost equalities during the transition to a decarbonised system.

Increasing the accuracy of cost distributions associated with the consumption of renewable electricity may also provide secondary gains. Aside from reducing the level of revenue required to remunerate RES-E generation in an exporting country, this approach may lower the economic barriers surrounding the cost to consumers of developing higher levels of RES-E capacity. If, for example, a country has the correct topography and climate for hydro-powered generation, then the cost as well as the benefit of this renewable energy source can be shared with neighbouring nations – aligning with aspects present in the Renewable Energy Directive around subsidy sharing, joint projects and statistical transfers, improving investment signals and issues surrounding long-term security of electricity supply.

The complexity associated with quantifying RES-E based on the proposed approach will be significantly higher than the status quo. The alternative is to continue to use, what may be perceived as an increasingly inaccurate methodology. Measuring RES-E by production may be viewed as a ‘quick and easy’ approach, however as electricity markets worldwide become more intrinsically linked and transition toward a de-carbonised sector with high renewable generation capacity, simplicity may no longer be the correct strategy for reasons alluded to.

Acknowledgements

The authors acknowledge the financial support provided by Bord Gáis Energy and the suggestions and help provided by Tomás Mac Uidhir of UCC.

References

Bahar, H., Sauvage, J., 2013. Cross-Border Trade in Electricity and the Development of Renewables-Based Electric Power: Lessons from Europe. OECD Trade and Environment Working Papers 2013, 0_1.

Booz & Co., Newbery, D., Strbac, G., Pudjianto, D., Noël, P., LeighFisher, 2013. Benefits of an Integrated European Energy Market, Prepared for the Directorate-General Energy. European Commission, Brussels.

Buchan, D., Keay, M., 2016. EU energy policy – 4th time lucky? The Oxford Institute of Energy Studies.

Byrnes, L., Brown, C., Foster, J., Wagner, L.D., 2013. Australian renewable energy policy: Barriers and challenges. Renewable Energy 60, 711-721.

Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., Evangelopoulou, S., Zampara, M., Papadopoulos, D., Nakos, C., 2016. EU Reference Scenario 2016-Energy, transport and GHG emissions Trends to 2050.

Cleary, B., Duffy, A., Bach, B., Vitina, A., O’Connor, A., Conlon, M., 2016. Estimating the electricity prices, generation costs and CO2 emissions of large scale wind energy exports from Ireland to Great Britain. Energy Policy 91, 38-48.

Collins, S., Deane, J.P., Ó Gallachóir, B., 2017. Adding value to EU energy policy analysis using a multi-model approach with an EU-28 electricity dispatch model. Energy 130, 433-447.

Couture, T., Gagnon, Y., 2010. An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. Energy Policy 38, 955-965.

Daly, P., Flynn, D., Cunniffe, N., 2015. Inertia considerations within unit commitment and economic dispatch for systems with high non-synchronous penetrations, PowerTech, 2015 IEEE Eindhoven. IEEE, pp. 1-6.

Deane, P., Chiodi, A., Gargiulo, M., Ó Gallachóir, B., 2012. Soft-linking of a power systems model to an energy systems model. Energy 42, 303-312.

Deane, P., Driscoll, A., Ó Gallachóir, B., 2015. Quantifying the impacts of national renewable electricity ambitions using a North–West European electricity market model. Renewable Energy 80, 604-609.

Denny, E., Tuohy, A., Meibom, P., Keane, A., Flynn, D., Mullane, A., O'malley, M., 2010. The impact of increased interconnection on electricity systems with large penetrations of wind generation: A case study of Ireland and Great Britain. Energy Policy 38, 6946-6954.

Dobos, A.P., 2013. PVWatts version 1 technical reference. National Renewable Energy Laboratory, Golden, CO.

Drayton, G., McCoy, M., Pereira, M., Cazalet, E., Johannis, M., Phillips, D., 2004. Transmission expansion planning in the Western interconnection-the planning process and the analytical tools that will be needed to do the job, Power Systems Conference and Exposition, 2004. IEEE PES. IEEE, pp. 1556-1561.

Durand, É., Keay, M., 2014. National support for renewable electricity and the single market in Europe: the Alands Vindkraft case. Oxford Institute for Energy Studies, August.

EirGrid & SONI, 2010. All Island TSO Facilitation of Renewables Studies, Tech. Rep.

EirGrid & SONI, 2011. Ensuring a Secure, Reliable and Efficient Power System in a Changing Environment.

ENTSO-E, 2012. Consumption Data. ENTSO-E, Brussels.

ENTSO-E, 2015. Ten-Year Network Development Plan 2016. ENTSO-E, Brussels.

EURELECTRIC, 2016. Electricity market design: fit for the low-carbon transition. EURELECTRIC, Brussels.

European Commission, 2009a. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009, on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, European Union, online at: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028.

European Commission, 2009b. Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54. OJ L211/55 14, 8.

European Commission, 2013. Guidance for the design of renewable support schemes - Commission staff working document. SWD(2013) 439 final. European Commission, Brussels.

European Commission, 2015. Paris Agreement. European Commission, Brussels.

European Commission, 2016a. Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast), COM(2016) 767 final - 2016/0382 (COD). European Commission, Brussels.

European Commission, 2016b. Proposal for a Regulation of the European Parliament and of the Council on the internal market for electricity, COM(2016) 861 final - 2016/0379 (COD). European Commission, Brussels.

European Commission, 2017. Renewables: Europe on track to reach its 20% target by 2020, European Commission - Fact Sheet.

Eurostat, 2015. SHARES Tool Manual Version 2015.70124. Eurostat, European Commission.

Eurostat, 2016. European Statistics.

Fan, J.-L., Hou, Y.-B., Wang, Q., Wang, C., Wei, Y.-M., 2016. Exploring the characteristics of production-based and consumption-based carbon emissions of major economies: A multiple-dimension comparison. Applied Energy 184, 790-799.

Fouquet, D., Johansson, T.B., 2008. European renewable energy policy at crossroads—Focus on electricity support mechanisms. Energy Policy 36, 4079-4092.

Foxon, T.J., Gross, R., Chase, A., Howes, J., Arnall, A., Anderson, D., 2005. UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures. Energy policy 33, 2123-2137.

Fraunhofer IWES, 2015. The European Power System in 2030: Flexibility Challenges and Integration Benefits. An Analysis with a Focus on the Pentalateral Energy Forum Region. Analysis on behalf of Agora Energiewende. Fraunhofer-Institute for Wind Energy and Energy System Technology (IWES), Berlin, Germany.

Gaffney, F., Deane, J., Gallachóir, B.Ó., 2017a. A 100 year review of electricity policy in Ireland (1916–2015). Energy Policy 105, 67-79.

Gaffney, F., Deane, P., Ó Gallachóir, B., 2017b. Lessons from an island system: a case study on Ireland's electricity market and variable renewable integration. Energy Strategy Reviews (In Review).

Glachant, J.-M., Ruester, S., 2014. The EU internal electricity market: Done forever? Utilities Policy 31, 221-228.

Global Wind Energy Council & International Renewable Energy Agency, 2013. 30 Years of Policies for Wind Energy: Lessons from 12 Wind Energy Markets. IRENA, United Arab Emirates.

Gonzalez-Aparicio, I., Zucker, A., Carei, F., Monfori-Ferranio, F., Huld, T., Badger, J., 2016. EMHIRES dataset Part I: Wind power generation. European Meteorological derived HIgh resolution RES generation time series for present and future scenarios, in: Technical Report EUR 28171 EN; 10.2790/831549 (Ed.), JRC (Joint Research Centre) EU Commission and Emhires dataset.

Gore, O., Vanadzina, E., Viljainen, S., 2016. Linking the energy-only market and the energy-plus-capacity market. Utilities Policy 38, 52-61.

Henriot, A., Lavoine, O., Regairaz, F., Hiroux-Marcy, C., Gilmore, J., Riesz, J., Yuen, C., do Brasil, D., Salvador, M., Ziegler, H., 2013. Market design for large scale integration of intermittent renewable energy sources. CIGRE Technical Brochure.

Hvelplund, F., Østergaard, P.A., Meyer, N.I., 2017. Incentives and barriers for wind power expansion and system integration in Denmark. Energy Policy 107, 573-584.

International Energy Agency, 2016a. Re-powering Markets: Market design and regulation during the transition to low-carbon power systems, Electricity Market Series. IEA, Paris.

International Energy Agency, 2016b. Renewable Policy Update, Renewable Energy. IEA, Paris.

Ji, L., Liang, S., Qu, S., Zhang, Y.X., Xu, M., Jia, X.P., Jia, Y.T., Niu, D.X., Yuan, J.H., Hou, Y., Wang, H.K., Chiu, A.S.F., Hu, X.J., 2016. Greenhouse gas emission factors of purchased electricity from interconnected grids. Applied Energy 184, 751-758.

Joskow, P.L., 2008. Capacity payments in imperfect electricity markets: Need and design. Utilities Policy 16, 159-170.

Larsen, H.N., Hertwich, E.G., 2009. The case for consumption-based accounting of greenhouse gas emissions to promote local climate action. Environmental Science & Policy 12, 791-798.

Lehmann, P., Gawel, E., 2013. Why should support schemes for renewable electricity complement the EU emissions trading scheme? Energy Policy 52, 597-607.

Lund, H., Mathiesen, B.V., Liu, W., Zhang, X., Clark Ii, W.W., 2014. Chapter 7 - Analysis: 100 Percent Renewable Energy Systems, Renewable Energy Systems (Second Edition). Academic Press, Boston, pp. 185-238.

Lund, H., Quinlan, P., 2014. Chapter 8 - Empirical Examples: Choice Awareness Cases, Renewable Energy Systems (Second Edition). Academic Press, Boston, pp. 239-325.

McGarrigle, E., Deane, P., Leahy, P., 2013. How much wind energy will be curtailed on the 2020 Irish power system? Renewable Energy 55, 544-553.

Meyer, R., Gore, O., 2015. Cross-border effects of capacity mechanisms: Do uncoordinated market design changes contradict the goals of the European market integration? Energy Economics 51, 9-20.

N-SIDE, EUPHEMIA, Brussels.

Painuly, J.P., 2001. Barriers to renewable energy penetration; a framework for analysis. Renewable energy 24, 73-89.

Peters, G.P., 2008. From production-based to consumption-based national emission inventories. Ecological Economics 65, 13-23.

Price Coupling of Regions, 2016. EUPHEMIA: Description and Functioning, in: PCR (Ed.), EUPHEMIA Stakeholder Forum. EPEX Spot, Brussels.

Reddy, S., Painuly, J.P., 2004. Diffusion of renewable energy technologies—barriers and stakeholders’ perspectives. Renewable Energy 29, 1431-1447.

RES Legal, 2017. Legal Sources on Renewable Energy: Compare support schemes, in: RES_Legal (Ed.).

Roques, F.A., 2008. Market design for generation adequacy: Healing causes rather than symptoms. Utilities Policy 16, 171-183.

Sáenz de Miera, del Río González, P., Vizcaíno, I., 2008. Analysing the impact of renewable electricity support schemes on power prices: The case of wind electricity in Spain. Energy Policy 36, 3345-3359.

Scarpa, R., Willis, K., 2010. Willingness-to-pay for renewable energy: Primary and discretionary choice of British households' for micro-generation technologies. Energy Economics 32, 129-136.

Schaber, K., Steinke, F., Mühlich, P., Hamacher, T., 2012. Parametric study of variable renewable energy integration in Europe: Advantages and costs of transmission grid extensions. Energy Policy 42, 498-508.

Sensfuß, F., Ragwitz, M., Genoese, M., 2008. The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Policy 36, 3086-3094.

Shao, L., Chen, B., Gan, L., 2016. Production-based and Consumption-based Carbon Emissions of Beijing: Trend and Features. Energy Procedia 104, 171-176.

Simas, M., Pauliuk, S., Wood, R., Hertwich, E.G., Stadler, K., 2017. Correlation between production and consumption-based environmental indicators: The link to affluence and the effect on ranking environmental performance of countries. Ecological Indicators 76, 317-323.

Verbruggen, A., Fischedick, M., Moomaw, W., Weir, T., Nadai, A., Nilsson, L.J., Nyboer, J., Sathaye, J., 2010. Renewable energy costs, potentials, barriers: Conceptual issues. Energy Policy 38, 850-861.

Wiedmann, T., 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecological Economics 69, 211-222.

Table(s)

Table 1: The standardised generation characteristics applied[1]

Fuel Type	Capacity (MW)	Start Cost (€)	Min Stable Factor (%)
Biomass/waste	300	10000	30
Derived gas	150	12000	40
Geothermal heat	70	3000	40
Hydro (lakes)	150	0	0
Hydro (run of river)	200	0	0
Hydrogen	300	5000	40
Natural gas CCGT	450	80000	40
Natural gas OCGT	100	10000	20
Nuclear	1200	120000	60
Oil	400	75000	40
Solids	300	80000	30

Table 2: Fuel and carbon price assumptions

Fuel Type / Carbon	2030
Oil (€2010 per boe)	€90
Gas (€2010 per boe)	€52
Coal (€2010 per boe)	€18
Carbon - ETS (€2010 per Tonne)	€40

Table 3: Net renewable electricity flow transfer as a share of total electricity transfer[2]

AI-GB	**AT-CZ**	**AT-DE**	**AT-HU**	**AT-IT**	**AT-SI**	**BE-DE**	**BE-FR**	**BE-GB**	**BE-LU**
46%	15%	12%	23%	25%	25%	-10%	0%	0%	-9%
BE-NL	**BG-GR**	**BG-RO**	**CH-AT**	**CH-DE**	**CH-FR**	**CH-IT**	**CY-GR**	**CZ-DE**	**CZ-PL**
-1%	-13%	0%	-6%	6%	19%	24%	2%	-2%	0%
CZ-SK	**DE-DK**	**DE-FR**	**DE-LU**	**DE-NL**	**DE-PL**	**DE-SE**	**DK-GB**	**DK-NL**	**DK-NO**
0%	-12%	10%	6%	10%	4%	9%	43%	37%	-42%
DK-SE	**EE-FI**	**EE-LV**	**ES-PT**	**FI-SE**	**FR-AI**	**FR-ES**	**FR-GB**	**FR-IT**	**FR-LU**
34%	0%	-4%	-64%	0%	-18%	-14%	0%	-1%	0%
GR-IT	**HU-HR**	**HU-RO**	**HU-SI**	**HU-SK**	**IT-SI**	**LT-LV**	**LT-PL**	**LT-SE**	**NL-GB**
20%	-1%	-1%	-1%	0%	-1%	-3%	0%	-1%	1%
NO-DE	**NO-GB**	**NO-NL**	**NO-SE**	**PL-SE**	**PL-SK**	**SI-HR**			
79%	100%	98%	94%	0%	0%	0%			

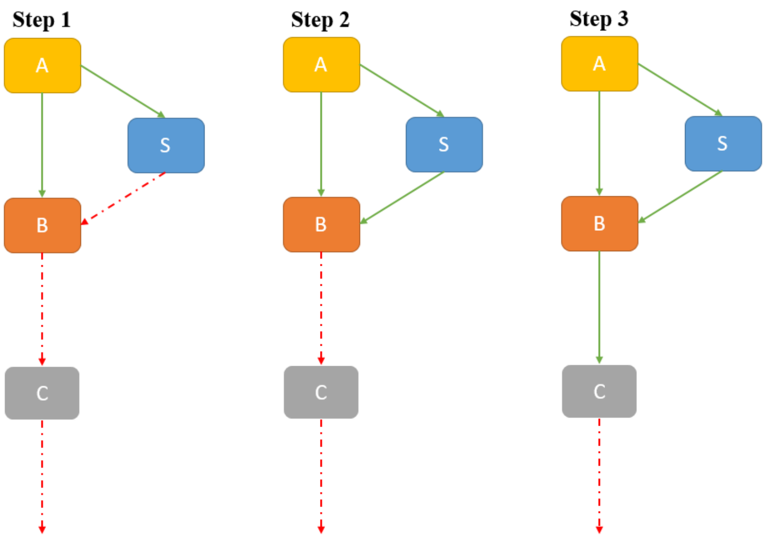
[1] Heat rates for the thermal categories represented in Table 1 are based on an individual country by country basis from the European Commission's Reference Scenario 2016.

[2] The table contains the electricity flows to and from the All-Island (AI) electricity system which consists of Ireland and Northern Ireland, along with Great Britain (GB).

Figure(s)

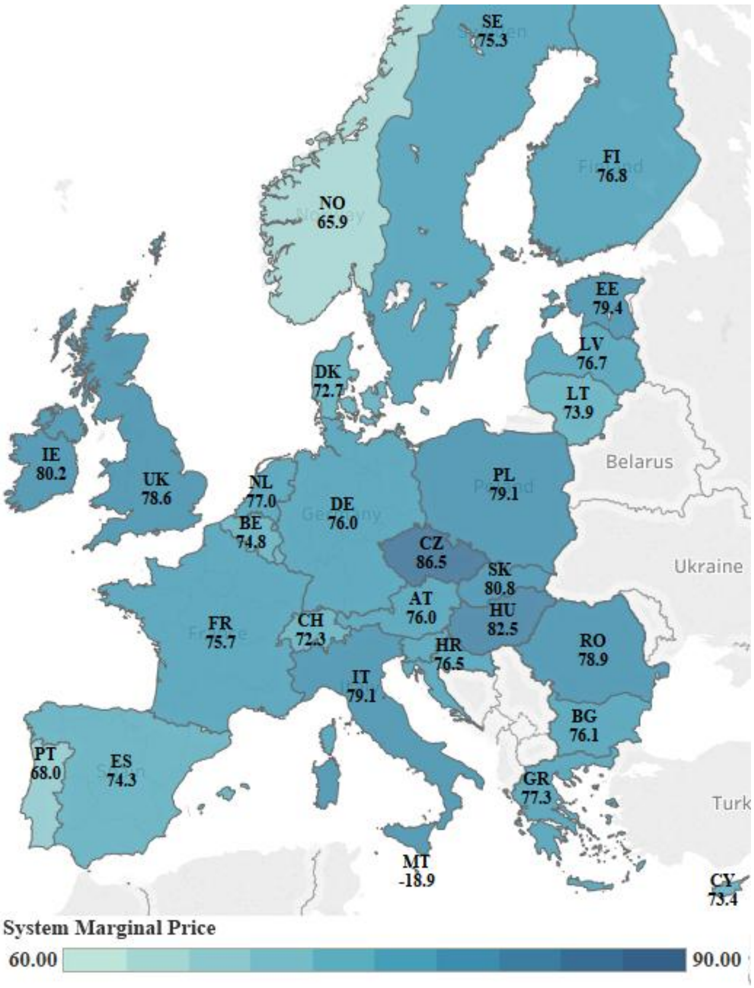
Figure 1: High-level view of interconnection capacity represented in the PLEXOS® model[1]

Figure 2: Illustrative example to explain the different steps undertaken



[1] Greece is also electrically connected to Cyprus. This interconnector is excluded from Figure 1 to maintain granularity around areas with the highest interconnection density.

Figure 3: Wholesale electricity prices of the EU-28 and two non-EU countries; Norway and Switzerland[2]



[2] Due to the aggregated nature of the generation portfolio, Malta experiences a non-optimal dispatch which results in numerous hours of negative pricing.

Figure 4: Interconnection activity between Portugal, Spain and France

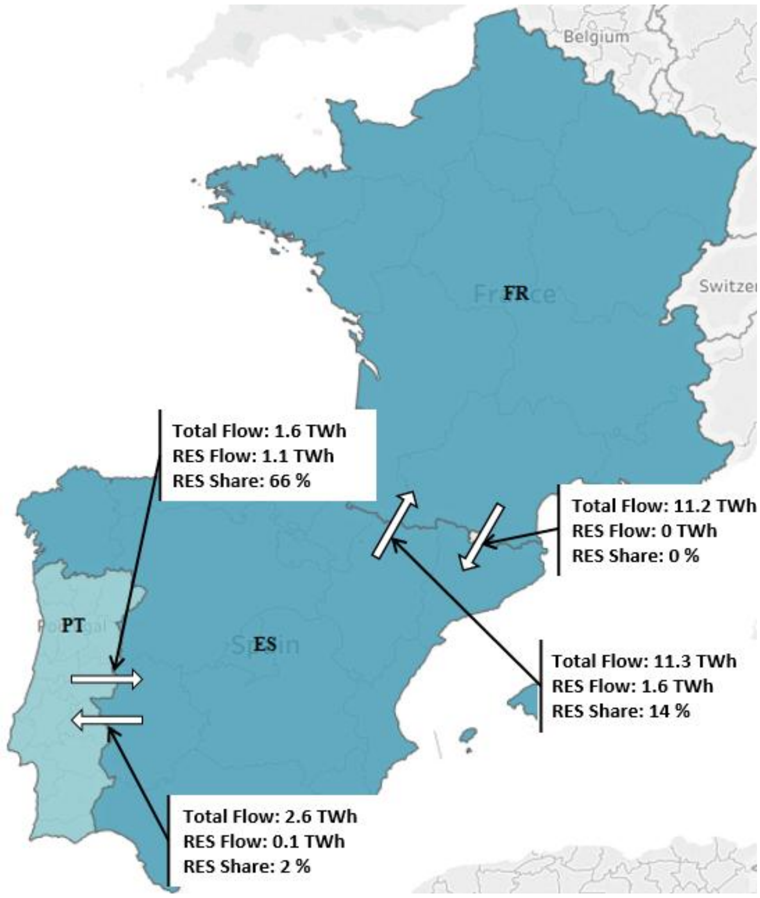


Figure 5: Interconnection activity between France, Germany, Denmark and Poland

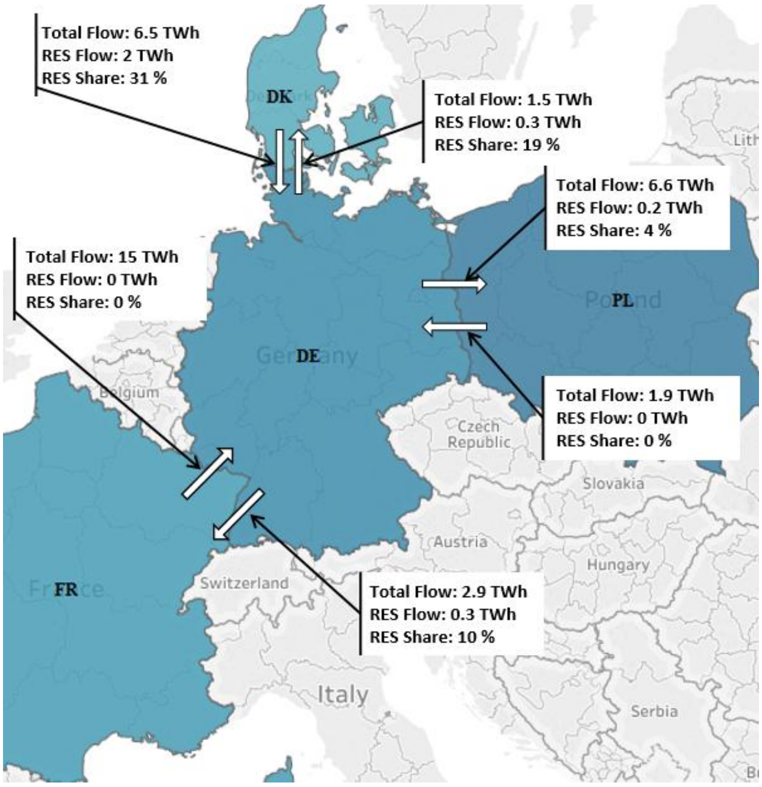


Figure 6: Interconnection activity between Norway, Denmark and the United Kingdom

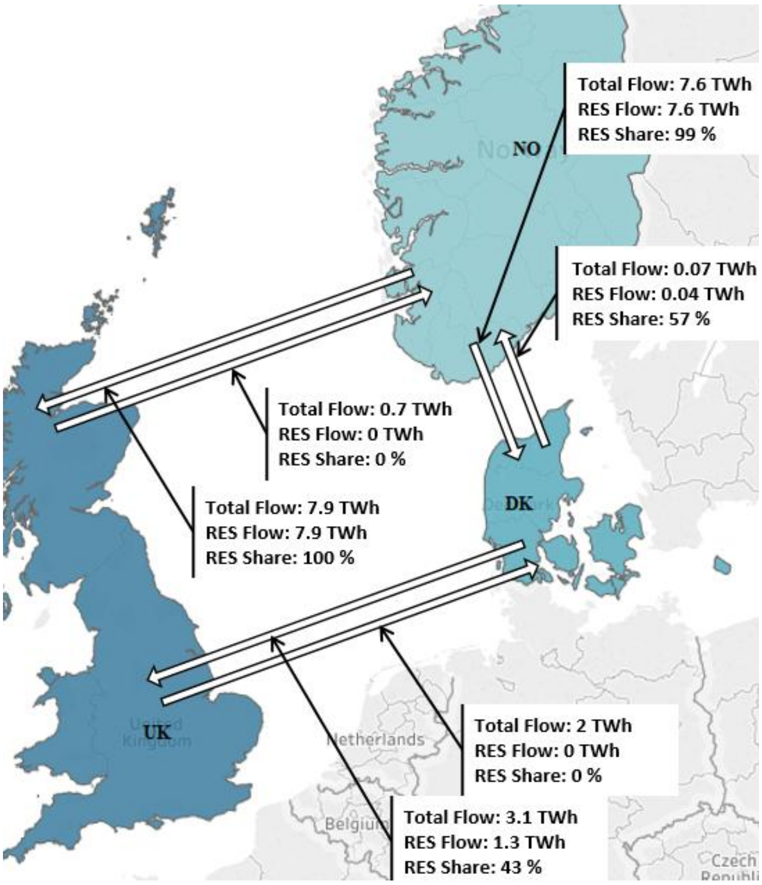
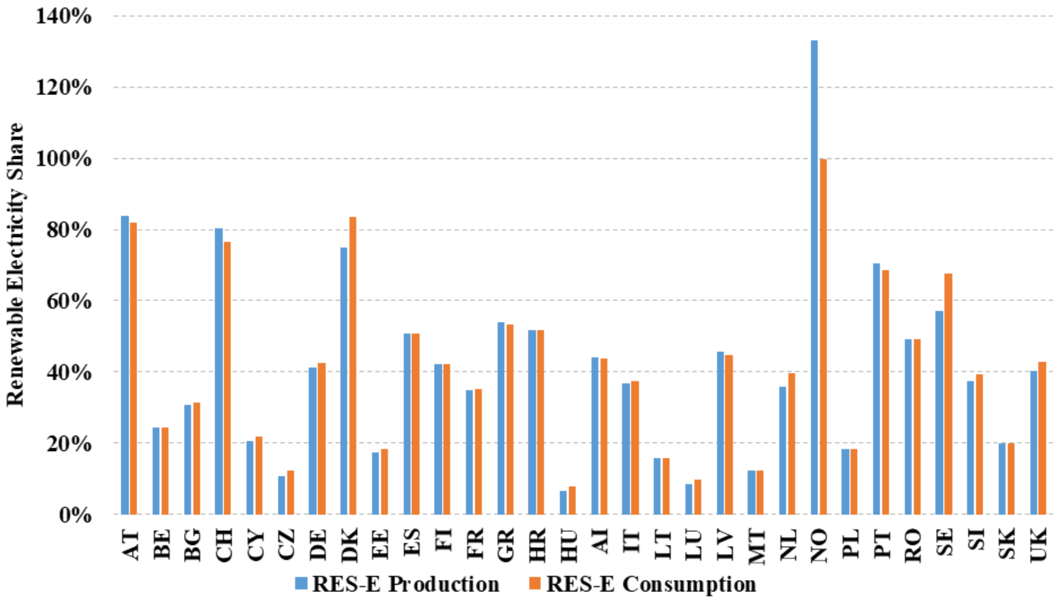


Figure 7: Comparing the RES-E share of 30 countries applying the traditional approach (RES-E production) and an alternative methodology proposed in this paper (RES-E consumption) [3]



[3] The simulation did not model generator "own use" or transmission and distribution losses, therefore Gross Final Consumption is unknown. In its place, the final electricity consumption is used to measure RES shares. For example, the RES-E Production is calculated using the renewable generation divided by the final electricity consumption of each country. RES-E Consumption uses the renewable generation plus renewable imports minus renewable export divided by final electricity consumption. It is recognised that this assumption is not aligned with the Renewable Energy Directive's methodology, however it provides an insight into the relative difference between the two approach which is the main point of the figure.

***Highlights**

- Consumption-based methodology to quantify RES-E is presented
- Consumption-based approach accounts for impact of RES-E imports & exports
- International agency could implement approach to address price distortions
- Policy is enhanced by enabling more equitable and optimal electricity decarbonisation