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The relative aggregate footprint of electricity generation technologies in the European Union (EU): A system of systems approach

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ABSTRACT

Decarbonizing electricity risks unintended consequences for other environmental resources. The European Union's (EU) Member States (MSs) embarked on a decarbonization and renewables deployment program aware of this risk. However, uncertainty remains around which technologies are best suited to the nexus of resources affected. In this study, we illustrate the benefits of using the Relative Aggregate Footprint (RAF) concept to evaluate energy technology alternatives. The RAF is an indicator based on a System of Systems approach that assesses technologies along multiple performance criteria, takes account of performance uncertainty, adjusts criteria importance according to local resource availabilities, and makes the evaluation robust to differing notions of optimality to determine the desirability of technologies. We evaluated 11 electricity generation technologies by cost, carbon, water and land footprint. Assuming equal weightings of the four criteria, we found nuclear, geothermal, and onshore wind to generally have the lowest RAF. We then calculated the MS-specific RAF's by weighing each criterion based on the local availability of the respective resource: 1) gross domestic product per capita, 2) carbon emissions per capita, 3) freshwater withdrawals as a share of renewable freshwater, and 4) land availability per capita. By analyzing variances between MSs' RAFs we highlighted how differences in resource availability generate trade-offs for EU electricity decarbonization policies.

1. Introduction

To fulfill duties under United Nation's (UN) climate treaties and contribute to avoiding dangerous climate change, the successive administrations of the European Commission (EC) have pursued policies for reducing greenhouse gas (GHG) emissions. The Barroso administration (2004–2014) set out a long term climate strategy in its communication, "A Roadmap for moving to a competitive low carbon economy in 2050″ (European Commission, 2011). It suggested an 80–95% reduction in GHG emissions by 2050. Enacted in 2009, the legal instruments of the 2020 Climate and Energy Package commit the EU Member States (MSs) to reducing the total EU GHG emissions by 20% by 2020, from 1990 levels (European Parliament and European Council, 2013). This legislation was built upon in the 2030 Climate and Energy Framework. Adopted in 2014, it targets a 40% reduction from 1990 levels by 2030 (European Council, 2014). Under the same legislation, targets are in place for increasing the share of renewables in the EU's energy mix to 20% of consumption by 2020 and 27% by 2030 (European Commission, 2011; European Council, 2014).

The EC highlighted how tools, which explore options for low-carbon pathways, lack a comprehensive integration of land-use and water systems (European Parliament and European Council, 2013). Integrated approaches to food security, low-carbon energy, sustainable water management and climate change mitigation are among the focuses of the EU Research and Innovation Programme (European Commission, 2015). The Union Environment Action Programme to 2020 highlights the importance of managing interactions between climate and other environmental objectives (European Parliament and European Council, 2013). If energy sector's decisions do not consider water management, land use and biodiversity, it is possible for climate policy outcomes to displace footprints and impacts from GHG emissions to other domains (Hadian and Madani, 2015; Maimoun et al., 2016; Ristic et al., 2015). For example, in a significant proportion of EU Member States, bioenergy is expected to provide a substantial contribution to meeting the renewable energy targets. Biomass energy is predicted to contribute 54.5% (including renewable heat and transport) to the 2020 renewable energy target with a contribution of approximately 20% within renewable electricity (mostly from solid biomass (wood)) (Beurskens and

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Hekkenberg, 2011). In light of the typically high land and water footprints of bioenergy, widespread adoption will place additional strain on land and water resources and introduce tougher competition with agriculture over land use. This necessitates the consideration of the secondary impacts of renewable energies such as biomass on water and land resources in Europe to identify the energy technologies that are most suitable though consideration of individual regional resource availability constraints and local concerns, in a bid to achieve a sustainable energy mix.

Although there is a substantial literature on external costs (Hadian and Madani, 2015; Madani and Khatami, 2015; Maxim, 2014; Streimikiene et al., 2012), few studies evaluate electricity technologies across multiple environmental impacts directly. Conclusions tend to differ across studies because of the lack of consensus on the conception of optimality, uncertainty in technology performance, and lack of an index enabling reliable aggregation (Madani and Khatami, 2015). Additionally, indicator-based approaches to technology assessment can be misleading if local circumstances are not appropriately accounted. A water intensive technology for example, should be avoided in a water stressed region while it can be entirely appropriate in a region benefiting from abundant water resources (Haghighi et al., 2018).

Europe is leading the way in the transition to low-carbon technologies. Nevertheless, the focus of EC in the short term is to reduce its GHG emissions through implementation of “cost- efficient ways”, which embraces the practices of EU policy, as well as the EU emissions trading system (EU ETS) (Delbeke et al., 2016). This in turn can lead to promotion of low-carbon technologies within Europe that exert additional burden on other valuable natural resources of the region such as water and land. This can create adverse impacts on the environment and lead to unintended consequences. Thus, there is a need for an approach that considers the environmental as well as economic impacts of technologies, whilst addressing local concerns and regional resource limitations. This approach is needed to highlight the cost-efficient technologies that are most suitable to each country based on their unique conditions, to cut greenhouse gas emissions while minimizing impacts on the environment. This in turn can identify suitable energy technologies that support the formulation of a sustainable plan in the long term, in line with each state’s commitments to carbon emission reduction.

To address these issues, here we apply the Relative Aggregate Footprint (RAF) concept (Hadian and Madani, 2015) for energy sustainability assessment in the EU. The key beneficial properties of the RAF that have been developed based on a System of Systems (SoS) approach are: 1) using multiple performance criteria or indicators; 2) taking performance uncertainties into account; 3) modulating the importance of different criteria according to local resource availabilities; and 4) using a range of multi-criteria decision-making (MCDM) methods during the assessment to make the results robust against different notions of optimality.

This rest of the paper is structured as follows. First, the methodology is described in detail, explaining the concept of RAF and the use of MCDM approach in obtaining the values of this index. The use of weights and their role in declaring resource intensity of each MS is explained in detail, along with the variances across RAFs. Secondly the results illustrate the differences between a generic, an EU-level, and a MS level assessment. This is then discussed more extensively to give a more nuanced understanding of EU energy planning, with regards to a generic, an EU-level, and a MS level assessment in the discussion. The findings are then discussed with regards to their policy implications for EU’s future development options. Conclusions are then drawn regarding the use and need of an integrated model that assess the sustainability of technologies with regards to their economic and environmental impacts across EU.

2. Methods

2.1. RAF

Based on a SoS approach, the RAF is a composite indicator determined by aggregating across multiple performance criteria using a Monte-Carlo MCDM approach involving a range of MCDM methods (Hadian and Madani, 2015). MCDM methods aggregate across multiple criteria to determine how the available alternatives compare. While different approaches to criteria selection can be used (Read et al., 2017), we assessed technologies on the basis of the following criteria: 1) levelized cost of energy, 2) carbon footprint, 3) water footprint and 4) land footprint, in accordance with the original definition of energy technology RAF (Hadian and Madani, 2015). Data collected on the former two technology performance criteria were mostly available from reports by the Intergovernmental Panel on Climate Change (Schlomer et al., 2014), while data for other performance criteria were drawn from other sources as shown in Table 1.

To account for technology performance uncertainties under different criteria, the MCDM process is repeated many times by a Monte-Carlo sampling with respect to different technology performance probability distributions. Based on a review of the literature on lifecycle analysis (Table 1), we determined the probability distributions of performance values for each criterion for each of the 11 electricity generation technologies considered. Rather than considering uniform distribution, as done earlier (Hadian and Madani, 2015), we used truncated normal distributions, when the median was not available or was close to the mean, and lognormal distribution otherwise. This improvement reduced bias arising from considering skewed distributions as uniform. For instance, carbon footprint values of hydropower have a long tail meaning the median would be much higher under uniform distribution, hence, unfairly representing the carbon footprint of hydropower. Performances under each criterion for each technology were sampled from these probability distributions and technologies were then ranked by each MCDM method. This process was run 100,000 times using a Monte-Carlo selection approach, with each run again sampling from the performance distribution.

Variety and disagreement exist over the best notion of optimality and its associated MCDM methods (Read et al., 2017; Triantaphyllou, 2000). Rather than choosing one method, the RAF is calculated using five different notions of optimality that serve as the base principle of five different MCDM methods in order to obtain robust results (Mokhtari, 2013):

1) Maximin: A technology with the highest performance under the worst performing criterion is considered the best.
2) Lexicographic: Criteria are ranked by importance. The technology that performs best under the most important criterion is chosen as the best option. If various alternatives are equal, the decision is made based on the second important criteria and so on until obtaining a unique solution.
3) TOPSIS: The best technology has the minimum distance from the best performance across all technologies under each criterion.
4) Simple Additive Weighting (SAW): Criteria are assigned weights by their importance. The technology with the highest weighted performance is the best option.
5) Dominance: Each alternative is compared to each other alternative under each indicator in pairwise-comparisons. The alternative that has won the most contests is the chosen one.

Further information on the MCDM methods can be found in Madani et al. (2014).

Table 1
Electricity generation technologies by carbon, water, land, and cost. Depending on data availability, values are given as a single value, a range defined by two values (min-max), or as a truncated log-normal distribution (min-mean-max) and the reference is given for each data source. (*a*: The oil price is determined by own computation based on values from an earlier study (Kost et al., 2013), but considering the minimum and maximum oil price between 2011 and 2016 and a discount rate of 10%, to be consistent with the IPCC data (Schlomer et al., 2014).) (*b*: As in (Hadian and Madani, 2015) land footprints of offshore wind are assumed to be the same as for onshore.).

Electricity Generation Technology	Carbon footprint (gCO_2eq/kWh)	Water footprint (m^3/GJ)	Land footprint (m^2/GWh)	Levelized Cost (USD_{2010}/MWh)
Biomass	130-230-420 (Schlomer et al., 2014)	20-64 (Gerbens-Leenes et al., 2009)	14433-21800 (McDonald et al., 2009)	77-150-320 (Schlomer et al., 2014)
Conc. Sol. P.	8.8-27-63 (Schlomer et al., 2014)	0.118-2.180 (Mekonnen et al., 2015)	340-680 (McDonald et al., 2009)	150-200-310 (Schlomer et al., 2014)
Solar PV	18-48-180 (Schlomer et al., 2014)	0.0064-0.303 (Mekonnen et al., 2015)	704-1760 (McDonald et al., 2009)	84-160-210 (Schlomer et al., 2014)
Wind: Onshore	7-11-56 (Schlomer et al., 2014)	0.0002-0.0012 (Mekonnen et al., 2015)	2168-2640 (McDonald et al., 2009)	51-84-160 (Schlomer et al., 2014)
Wind: Offshore	8-12-35 (Schlomer et al., 2014)	0.0002-0.0012 (Mekonnen et al., 2015)	2168-2640 (*b*)(McDonald et al., 2009)	110-170-250 (Schlomer et al., 2014)
Hydropower*	1-24-2200 (Schlomer et al., 2014)	0.3-850 (Mekonnen et al., 2015)	538-3068 (McDonald et al., 2009)	9-35-150 (Schlomer et al., 2014)
Coal	740-820-910 (Schlomer et al., 2014)	0.079-2.1 (Mekonnen et al., 2015)	83-567 (McDonald et al., 2009)	30-78-120 (Schlomer et al., 2014)
Oil	657-866 (WEC, 2004)	0.214-1.19 (Mekonnen et al., 2015)	1490 (McDonald et al., 2009)	85-224 (*a*)
Natural Gas	410-490-650 (Schlomer et al., 2014)	0.076-1.240 (Mekonnen et al., 2015)	623 (McDonald et al., 2009)	34-79-150 (Schlomer et al., 2014)
Nuclear	3.7-12-110 (Schlomer et al., 2014)	0.018-1.45 (Mekonnen et al., 2015)	63-93 (McDonald et al., 2009)	45-99-150 (Schlomer et al., 2014)
Geothermal	6-38-79 (Schlomer et al., 2014)	0.0073-0.759 (Mekonnen et al., 2015)	33-463 (McDonald et al., 2009)	18-89-190 (Schlomer et al., 2014)

Data references in brackets

* This study did not consider small hydropower due to lack of data.

The overall rankings of the alternatives under each MCDM method are not necessarily identical (due to different notions of optimality in each method). RAF was used here as an index to aggregate the overall desirability of energy alternatives across the MCDM methods (Hadian and Madani, 2015). RAF aggregates the ranks a technology achieves under each MCDM into an index ranging from 0 to 100 according to the following equation (Hadian and Madani, 2015):

$$RAF_i = 100\left[1 - \left(\frac{CN - B_i}{N(C-1)}\right)\right] \tag{1}$$

where C is the number of alternatives; N is the number of MCDM methods; B_i is the sum of ranks assigned to technology i under each MCDM; and RAF_i: Relative Aggregate Footprint of alternative *i*. The value of this index gives each technology's desirability relative to other technologies. The lower the RAF of a specific technology, the more desirable that technology. As the index value is normalized over the number of MCDMs and technology alternatives, when RAF = 0 that technology is strictly dominant, meaning it is better than all alternative technologies according to all MCDM methods. Where RAF = 100, that technology is strictly dominated as it is worse than any other according to all MCDM methods.

We first assumed equal weightings of the criteria to get generic RAF values as has been done in a previous RAF assessment study (Hadian and Madani, 2015). We then conducted a sensitivity analysis of electricity technologies' RAFs, highlighting criteria driving RAF values for each technology and which technology RAFs are more (or less) robust to MS resource availability (i.e. the potential significance of economic, water, land, and carbon budgets to the desirability of different technology options). To conduct a sensitivity analysis, we recalculated RAF values for all combinations of the evaluation criteria (for example: only cost, only carbon footprint, cost and carbon, etc.) This gave an overview of each technology's RAF under any subset of the four sustainability criteria considered. Subsequently, we used national resource availabilities to set criteria weights for EU MS-specific RAF values.

The RAF does not consider the feasibility of a technology. The lower a technology's RAF value, the more desirable it is due to its lower footprint. Excluding feasibility in this way allowed us to avoid making uncertain assumptions about the technical, physical, socio-economic, and political conditions and parameterizations (see Discussion.)

2.2. Setting criteria weights

We set criteria weights based on the resource availability and resource use intensity of each MS. A MS using large shares of renewable freshwater, may be more concerned by water footprint than a MS using only a small share of its renewable freshwater. This gave us insight into how the different resource availabilities affect the desirability of electricity generation technologies across MSs.

We considered four resource availability metrics as shown in Table 2 (carbon emissions per capita, freshwater withdrawals as a share of renewable water resources, km^2 of available land per capita, and gross domestic product in dollars per capita). We used World Bank data except for freshwater where we used Food and Agricultural Organization's (FAO) Aquastat data (Food and Agriculture Organisatioon, 2016; The World Bank, 2017). This is in line with our other data also being sourced from UN institutions.

We used MS rankings in global league tables for each resource availability indicator for setting MS-specific criteria weights. The ranges were split into 5 percentile bands: 0 to 20; 20 to 40; 40 to 60; 60 to 80; 80 to 100. These 5 bands were assigned a score from 1 to 5. For each member state we used a criterion's share of the sum of all criteria scores to calculate its weight. The higher carbon emissions per capita or the freshwater withdrawals as percentage of renewable water resource, the greater the weight for the respective criteria. For available land per capita and for GDP per capita (PPP), higher values meant a lower

Table 2
Available resources of the EU member states.

EU Member State *Data source*	Carbon emissions (metric tons per capita) (The World Bank, 2017)	Freshwater withdrawal as % of renewable water resources (Food and Agriculture Organisatioon, 2016)	Available land area (km^2 per capita)* (The World Bank, 2017)	Economic power (GDP per capita, PPP (international $)) (The World Bank, 2017)
Austria	6.87	4.49	0.0094	50644.43
Belgium	8.33	32.80	0.0027	46541.37
Bulgaria	5.87	26.43	0.0152	19508.97
Croatia	3.97	0.60	0.0134	23731.77
Cyprus	5.26	28.44	0.0079	32580.35
Czech Republic	9.17	12.55	0.0073	35139.58
Denmark	5.94	10.62	0.0074	49818.80
Estonia	14.85	13.43	0.0322	29620.04
Finland	8.66	5.97	0.0553	43365.07
France	4.57	14.13	0.0082	41466.27
Germany	8.89	21.42	0.0042	48884.76
Greece	6.18	14.02	0.0120	26525.90
Hungary	4.27	4.86	0.0092	26996.81
Ireland	7.38	1.46	0.0144	71404.71
Italy	5.27	28.10	0.0049	38345.14
Latvia	3.50	0.68	0.0317	25932.54
Lithuania	4.38	2.56	0.0218	29966.13
Luxembourg	17.36	1.23	0.0044	103556.59
Malta	5.49	44.36	0.0007	38072.13
Netherlands	9.92	11.78	0.0020	51319.52
Poland	7.52	18.96	0.0081	27922.68
Portugal	4.33	11.82	0.0089	30664.88
Romania	3.52	3.03	0.0117	23626.37
Slovak Republic	5.66	1.12	0.0089	30706.10
Slovenia	6.21	3.63	0.0098	33421.24
Spain	5.03	32.96	0.0108	36462.11
Sweden	19.46	1.55	0.0411	49507.85
United Kingdom	6.50	5.45	0.0037	43080.96

* This is simply area/population and it misses an accurate representation of available land per person. It is an assumption that total area of the country is habitable, and that a simple division provides an estimation of land available in the state per person of its population.

weight for their respective criteria.

2.3. Variance across RAFs

Finally, our analysis considered the variance across MS-specific RAFs to show which technologies have similar RAF values across MSs and for which technologies there is greater divergence over RAF values. The variance (σ2) of the RAF value of each technology, i.e. the sum of squared differences between each MS's RAF value and the EU-level average RAF for that technology, indicates the degree of divergence between technology RAFs across MSs. The discussion relates variance to electricity supply portfolio optimization (Hadian and Madani, 2014), and to how the EU's decarbonization program could account for differences between MSs to harness the benefits and avoid the risks of harmonization in decarbonization policy.

3. Results

3.1. RAF sensitivity to Resource availability

Fig. 1a shows the RAF analysis results with all criteria (levelized cost, carbon, water, and land footprint). When all criteria were considered equally, there were no strictly best (dominant) or strictly worst (dominated) technologies. This is caused by the uncertainties in performance values as well as the differences between the optimality principles of different MCDM methods. Having a non-zero RAF value suggests that there is disagreement between the MCDM methods in determining the absolute best option for the uncertain performance values and trade-offs. Likewise, the absence of RAF = 100 reflects the disagreement between the MCDM methods in determining the absolute worst option. The figure indicates that, given our input data (Table 1), nuclear and geothermal perform relatively better than the other technologies. The worst relative performers are biomass, oil, and large-scale hydropower.

RAFs here are entirely driven by the data sources for the criteria performances and in the sensitivity analysis the driving criteria will be clearly identified. Consideration of different data or criteria performance assumptions, RAFs would almost certainly change.

The results of our sensitivity analysis are depicted in Fig. 1b–f. The larger the colored area, the worse a technology's relative performance generally. Nuclear (Fig. 1b) has a small area indicating a low (good) RAF in general, while biomass (Fig. 1f) has a large area indicating the opposite. The smoother the edge of the colored area, the less sensitive the relative performance to different combinations of evaluation criteria, i.e. the change in desirability is less sensitive to local resource availability conditions. Under certain criteria combinations, some technologies received RAF values of 100, meaning they were strictly dominated, while some received RAF values of 0, portraying their dominance.

When considering carbon and land footprint individually or in combination, nuclear power was strictly dominant. When only carbon, land and water footprints were considered, nuclear power was also strictly dominant. These dominance relations led to nuclear outperforming most other technologies most of the time and showed the extent to which good performance of nuclear power was not sensitive to changes in criteria weightings and hence its desirability is relatively robust to criteria selection and resource availability conditions. Under this assessment, nuclear's slight weakness is in its mid-range water footprint and relative high cost. While this may indicate that nuclear is a very good option for most countries, there are other reasons not included in the RAF calculations which may preclude its adoption such as political acceptability and public perception. Geothermal also had a very low RAF when all criteria were considered. Carbon emissions reduction from geothermal is the priority area for further development of

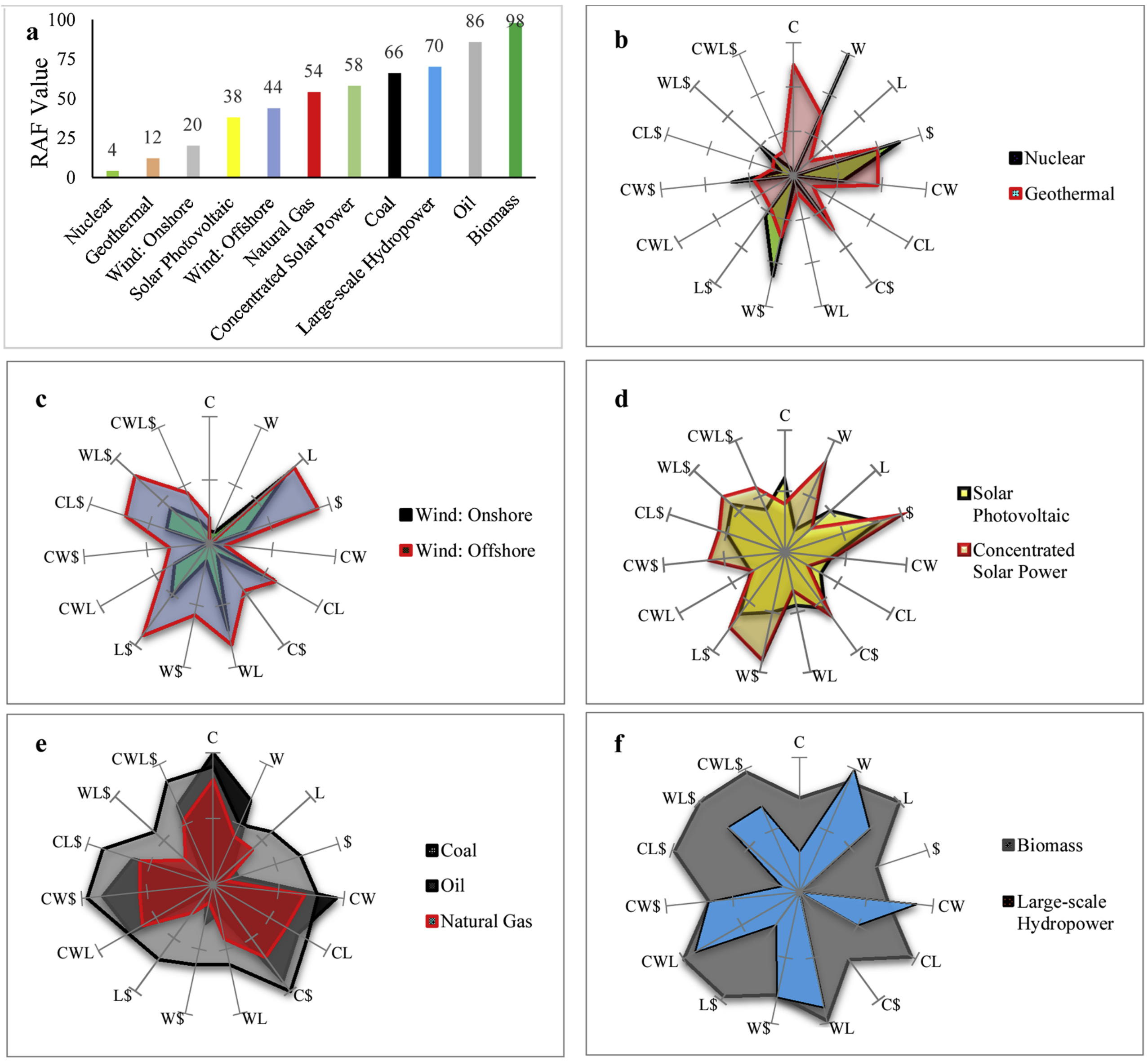

Fig. 1. Sensitivity analysis of the RAF of electricity generation technologies. Panel **a** represents the RAF values for each technology under all criteria when equally weighed. Panels **b–f** show RAF from 0 in the center to 100 at the periphery of the radar chart. The different combinations of the criteria are identified by the following code: ($: cost; L: land; W: water; C: carbon).

this technology as it showed a mid-range RAF when only this criterion was considered.

Although wind power was not strictly dominant in any category, both the onshore and offshore variants perform particularly well when only water and carbon footprint were considered (Fig. 1c). However, both wind technologies have high land footprints (high ecological footprint in case of offshore wind which is assumed to be equal to onshore land footprint (Hadian and Madani, 2015)), while offshore wind also suffers from high costs. Their desirability is thus sensitive to resource availability conditions. Solar technologies (Fig. 1d) on the other hand, suffers from high costs with concentrated solar power (CSP) strictly dominated when only costs were considered. The costs of these technologies are therefore a priority for further research and development whilst CSP is also disadvantaged by its high water footprint, which can be further improved in future advancements.

Hydrocarbon fuels (Fig. 1e) have high carbon footprints, with coal strictly dominated when carbon is the only criteria considered. Oil is strictly dominated when carbon and costs were considered. However, coal has the best relative performance when either cost and land footprint or cost, land footprint and water footprint were considered. Clearly, the research and development priority for these fuels is GHG emissions reduction through options such as carbon capture and storage technologies.

Natural gas is the best performing hydrocarbon with lower impact on carbon, water and land. Although it has the lowest carbon emission amongst the fossil fuels considered, its major drawback is its high emission in comparison to its impact on other indicators.

Biomass and large-scale hydropower (Fig. 1f) have poor performance in terms of water and land. Biomass was strictly dominated under 3 of the 15 combinations: 1) land footprint only, 2) water footprint, land footprint and cost, 3) carbon footprint, water footprint and land footprint. Large-scale hydropower however, was strictly dominant when only costs or only costs and carbon footprint were considered and strictly dominated when only water footprint was considered. Biofuels and hydropower both face research and development challenges in how to reduce their land and water footprints as these drive poor relative performance.

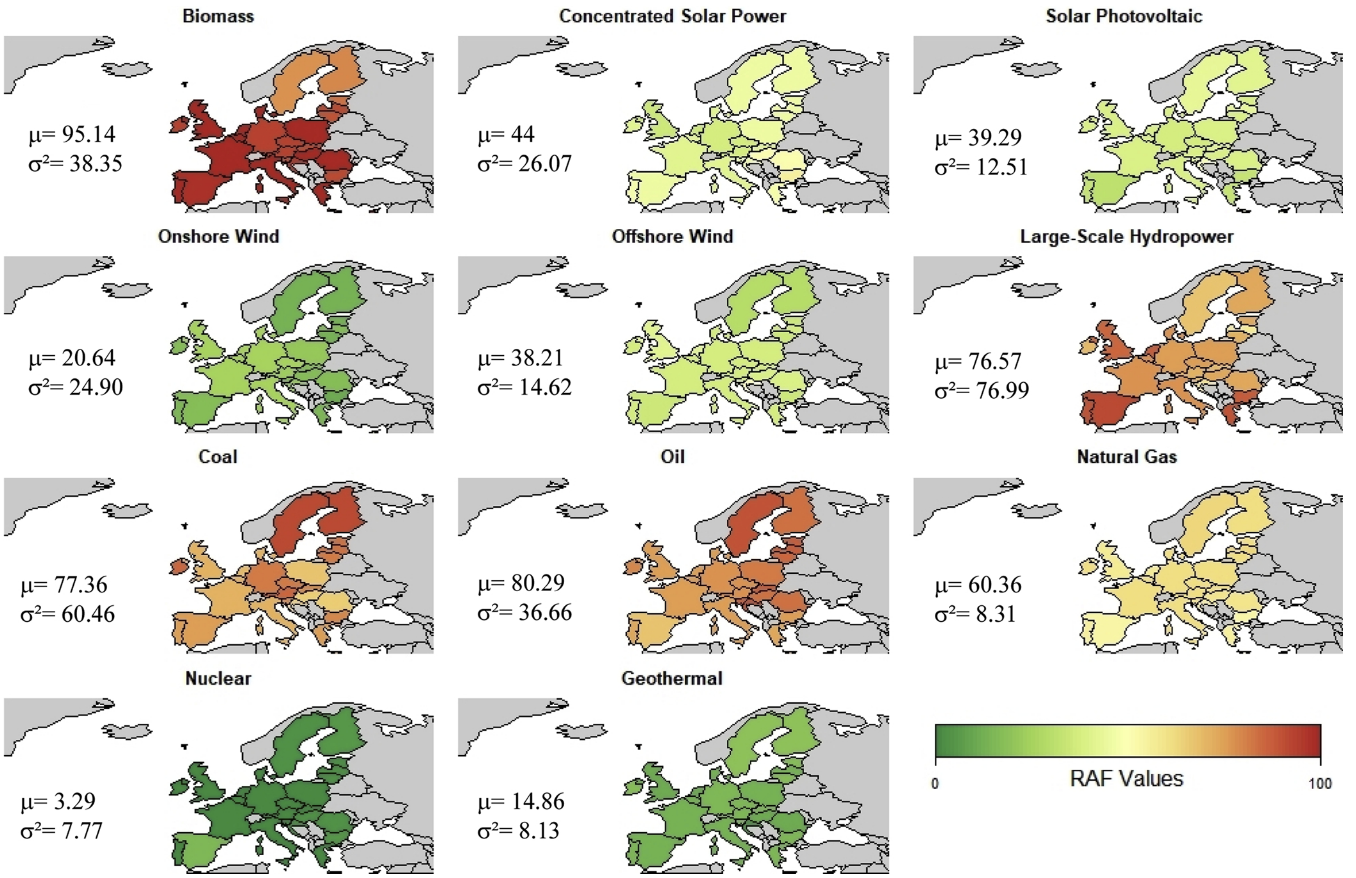

Fig. 2. Electricity technology RAF values across EU MSs. Dark green represents strictly dominant technology RAF = 0); dark red represents a strictly dominated technology (RAF = 100.) In the labels, μ indicates the mean MS RAF and σ^2 indicates the variance between MS's RAFs (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

3.2. Member State specific RAFs

By setting criteria weights according to the resource availability conditions in the EU, MSs illustrates how energy technology RAFs and regional desirability vary accordingly. Fig. 2 shows the RAFs of each electricity technology for each MS, with green indicating a low RAF and red a high RAF. While the general trend in technology RAFs across MSs was the same as when criteria were equally weighed, differences existed due to resource availability variations across the MSs. We analyzed these differences by considering the variances in MS-specific RAF values.

The variance (σ^2) of the RAF value of each technology, indicates the degree of divergence between technology RAFs across MSs. Nuclear has a low generic RAF and this value is not highly sensitive to different criteria combinations. Thus, we found nuclear to have the lowest variance around a low EU-level RAF. Similarly, low variance was observed in the EU average RAF for geothermal, natural gas, solar PV and offshore wind. On the other hand, RAF valuations across MSs showed the highest variance over large-scale hydropower and coal, indicating these are the most controversial technologies in terms of MS-specific RAFs.

RAFs from Croatia, generally deviated most from the EU average RAFs, closely followed by Bulgaria, Spain and Sweden. Forty nine percent of the variance around hydropower's EU RAF is due to Latvia and Spain, which give much lower (58) and much higher (92) RAFs for large-scale hydropower, respectively than other MSs. The varying water availability in these countries was the key driver of these differences from the EU level average. The second largest variance was in the MS-specific RAFs assigned to coal. Sixty percent of the variance around coal was due to Sweden and Finland's much higher RAFs and Hungry and Romania's lower RAFs for coal than the EU average, largely due to their relatively high and low GDP per capita, respectively.

4. Discussion

As has been argued before, assigning monetary valuations to environmental resources is highly contentious (Hamed et al., 2016) and does not give a reliable commensuration method. Assessment criteria based on physical performance values (e.g. water footprint) in addition to cost indicators offer a more robust approach to evaluating technology performance and desirability. However, a multi-criteria approach engenders the question of how the criteria are to be aggregated given each has its own unit of measurement and the lack of consensus over the selection of the most reliable MCDM method. The RAF method gives an answer to these problems with its simultaneous application of multiple MCDM methods.

A related aspect of aggregation across multiple criteria is that of criteria weighting. Weight-setting is subject to substantial controversy since weights are effectively arbitrary parameters with a potentially decisive influence on aggregation outcomes. To address this issue, we conducted a sensitivity analysis to identify which valuations are sensitive to changes in criteria selection and which are robust. This showed the low RAF values for nuclear and geothermal to be broadly robust to criteria selection. An ancillary benefit of the sensitivity analysis was to identify priority areas for technology-specific research and development. Both wind technologies, for example, were found to be very sensitive to land footprint being included, whilst offshore wind was equally sensitive to costs. Likewise, a relatively high RAF for large-scale hydropower was found to be driven by the inclusion of land, and even more so, water footprint. Research and development in these technologies could then prioritize performance improvements in the criteria driving high RAF.

Data used in this study found RAF values under all criteria equally weighed (Fig. 1a) to be only slightly different from a previous SoS study (Hadian and Madani, 2015). Biomass, oil and coal performed poorly while geothermal energy was found to perform very well in both SoS studies. Our study found nuclear to have a lower RAF than the previous SoS study while biomass and hydropower fared worse with the updated data. The undesirability of biomass is borne out by another study using a comparable methodology which did not consider water footprint but did include a series of other indicators not considered here. The study mentioned (Maxim, 2014), also declared large hydroelectric projects to be the most sustainable energy alternative, through consideration of a series of slightly different sustainability indicators. However, given their exclusion of water footprint, and the major role the high-water footprint of this technologies plays in its undesirability, proves the importance of holistic sustainable assessment of technologies, through various systems.

The method we employed to reflect local conditions in technology assessment sought to leverage the power of weight-setting in MCDM to reflect MS resource conditions on technology desirability. We showed how inclusion of local conditions can at times engender considerable divergence in technology desirability across MSs. By calculating variances between MS-specific RAF's we could identify technologies over which the greatest differences exist in terms of desirability. We could also identify the MSs which were the drivers of that variance. Our method and findings are directly relatable to the EU's electricity generation portfolio as a whole and its decarbonization pathways. While specific portfolio recommendations would require more analysis, some tentative conclusions can be drawn from our results.

Our results indicate low-carbon technologies are broadly preferable to hydrocarbons. This demonstrates that a transition from fossil fuels to renewables is likely to yield co-benefits for water and land as these technologies have better performances across these criteria. However, 19.1% of the EU's renewable electricity had been potentially set to come from biomass by 2020 (Beurskens and Hekkenberg, 2011). Biomass currently constitutes 54.5% of renewable energy targets (Atanasiu, 2010). Our results demonstrate that 13 out of 28 MSs have ranked biomass as the ultimate worse energy technology (RAF = 100). This means that the transition is not likely to fully benefit from those co-benefits as biomass is resource intensive in terms of its water and land footprint (Hadian and Madani, 2013). In light of the potentially high land and water footprints of bioenergy, its widespread adoption could burden land and water resources and harshen land-use trade-offs with agriculture or other sectors. That being said, some second generation bioenergy fuels are showing lower footprints in these criteria, indicating the potential for improvement in the RAF of bioenergy (Mathioudakis et al., 2017).

We found very low RAFs for nuclear for the majority of the MSs. In 2014, nuclear had the largest single share (27.9%) of any fuel type in the EU's electricity portfolio (Eurostat, 2017). While this technology has a substantial share of the EU electricity portfolio, generation from nuclear energy is on a downward trajectory with a decline of 13.1% over the ten years since its peak in 2004 (Eurostat, 2016). Multiple barriers facing this technology impede further growth of its share in the electricity mix despite its apparent desirability based on the criteria we considered. Public perception of the risks of nuclear energy is arguably the main barrier and varies substantially across EU member states. France is almost entirely reliant on nuclear. The country derives approximately 75% of its electricity using Nuclear energy. However France placed a target to reduce this share to 50% by 2025(World Nuclear Association, 2018a). In spite of this, in 2017, during COP23 in Bonn, Macron's government announced that this target will not be honored by 2025. It is believe France is working towards achieving this target by 2030 or 2035 (Haeringer, 2017; Wright, 2017). Whilst Germany's Green Party and environmentalist movement have a history of anti-nuclear sentiment, in 1998 a coalition government featured a policy to phase out nuclear, which was cancelled by the new government of 2009, but reintroduced in 2011. This resulted in immediate closure of 11 reactors (World Nuclear Association, 2018b). Public perception of nuclear also worsened substantially after the meltdown in Japan's Fukushima Daiichi nuclear power station in 2011. In terms of quantitative analysis, a key concern for nuclear energy is the long timelines for managing nuclear waste and decommissioning. Alongside the question of appropriate discount rates for such long planning horizons and associated problems of inter-generational equity, reasonable disagreement may exist over how to assess the impacts, risks, and desirability of nuclear energy. These social and scientific issues are not always easily quantifiable but are important to include in evaluating the good relative performance we found for nuclear.

Following nuclear, geothermal has the lowest RAF across EU's MSs and very low variances across the region. In 2013, EU was estimated to have a potential of 6 TW h electricity production from geothermal whilst the NREAP forecasted a production of 11 TW h, 174 TW h and over 4000 TW h in 2020, 2030 and 2050 respectively (van Wees et al., 2013). Thus, our results indicate this to be a transition in the right direction due to high desirability of geothermal in accordance to environmental and economic indicators considered.

We found offshore wind to have one of the lower variances among MSs. In 2014, wind power constituted approximately 8% of total EU electricity production (Eurostat, 2017). Although only a very small proportion of it is offshore, wind power has been the most rapidly growing renewable source of electricity (Wind Europe, 2016). Conversely, we showed that variance was highest for coal and hydropower. For coal the main driver was the difference between the MSs of Northern Europe (i.e. Sweden and Finland) and Eastern Europe (i.e. Croatia, Romania and Hungry). For Sweden and Finland, coal is highly undesirable due to Sweden's extremely high emissions and Finland's high emission combined with its high-water use. For Croatia, Romania and Hungry coal is more desirable due to their lower carbon emissions and economic capacity. On the other hand, for hydropower the difference between Northern Europe (i.e. Spain, Portugal, Malta and Greece) and Southern Europe (i.e. Latvia and Croatia) were the main drivers of this high variance. Hydropower was highly desirable in Latvia and Croatia due to the higher water availability, and lower economic power. Whilst in Northern European countries, due to their significantly higher water use, the technology is deemed highly undesirable. These were the largest divergences although others were also found. For example, Spain's RAF for nuclear was found to be much higher that of most other MSs raising the variance of nuclear energy. As seen in Fig. 1b, nuclear's performance is sensitive to water footprint. Thus, Spain, is highly water stressed, which makes nuclear less desirable in Spain compared to the rest of the region.

The implication of the high variances is that the transition to low carbon energies will require taking special account of regions that are water stressed and less economically developed. These regions are the ones where technological change away from hydrocarbon fuels is potentially more likely to be hampered by local constraints. Clearly, ignoring such variability across MS's conditions can lead to the promotion of technologies inappropriate to those regions and subsequent unintended consequences.

Attempting an assessment integrating the multiple systems we considered is fraught with complexity and opportunities for misjudgment abound. Hence, we did not set out to provide the definitive solution to the complex set of problems involved. Instead, we provided an illustrative application of the RAF concept to highlight the importance of multiple assessment criteria, performance uncertainty and trade-offs, as well as local conditions to technological desirability. The RAF has the added methodological benefit of delivering an assessment robust to differing notions of optimality in multi-criteria aggregation. Applying the RAF concept, we were able to give an illustrative appraisal of the desirability of different electricity generation technologies at the scale of EU's MSs. More work remains to be done to refine the analysis, the policy implications of our results and how future work could overcome the limitations of this study.

A previous study of energy decarbonization was heavily criticized for unrealistic assumptions about the feasibility of assumed capacity deployment rates, the lack of an appropriate electricity grid model, and other issues (Clack et al., 2017). Our study did not seek to model the EU energy system or provide a concrete decarbonization pathway. Instead, our purpose was to highlight the multiple systems that should be considered and how this could be done. Clearly, the lack of a grid model and wider energy system is a limitation of our study. The scale at which technologies can be deployed and feasibility constraints should also be included in a future portfolio analysis. This limitation however does not invalidate the need to assess the desirability of electricity technologies on the basis of the SoS approach we employed. For example, while Clack et al. (2017) discussed average power density in relation to the feasibility of capacity additions, our use of the related metric of land footprint was not as a feasibility constraint but as an indicator of one of the systems impacted by electricity generation. Future studies should seek to meaningfully incorporate feasibility constraints with a multi-criteria analysis of technology desirability. Given that significance of the social pillar of sustainability, in addition to economic, environmental and feasibility considerations, sustainability assessments of energy technologies in the future will also benefit from the inclusion of social constraints, as was discussed in case of nuclear energy.

A related limitation of our study is how technology components and complements were considered. Widespread deployment of renewables suffers from the challenge of managing its intermittent supply. Demand management, energy storage, and grid integration are some of the possible solutions that have been proposed to this issue (IEA, 2011; Mareda et al., 2017), and future RAF studies should seek to integrate these into modelling efforts. Thermal plant cooling systems, for example, could also be included in such an analysis as these are a major driver of fossil fuel water footprint.

A final set of limitations relate to the choice of data for technology performance, MSs' weightings, and geographic scale. Technology performance data were taken from global performance ranges and hence did not take variability due to local conditions into account. For example, climatic, regulatory, and other factors have been shown to have an important effect on water footprint (Mekonnen et al., 2015). Our data also did not consider expected changes in performance over time such as learning effects and economies of scale brought about by increased capacity deployment. Future studies should collate reliable parametrizations of these drivers of performance for a further refinement of the analysis and portfolio analysis. Future studies should also improve further on our method for location-specific criteria weighting. In particular, the use of local drivers of relative criteria importance should be used as opposed to global benchmarking approach we employed. For example, EU MSs have individual carbon reduction targets. The distance to achieving this target could be used as an indicator of the importance of low carbon footprint for each MS. Our findings suggest that energy planning must consider the local constraints and conditions. While here the focus was at the national scale, further refinement of geographic scale of evaluation can improve the assessment quality. Examples of such refinement include performance evaluation and weighting at the subnational, provincial, watershed, and district scales.

With these limitations in mind, our approach was to not make uncertain assumptions about feasibility and other issues raised above. Rather, we used data from the IPCC and other UN institutions which are widely accepted within the policy and scientific communities for illustrative purposes. Future studies should build on this approach to offer further policy insights for pathways suitable to the multiple systems impacted by decarbonization programs.

5. Conclusion

Under the SoS approach adopted, the desirability of a technology is not solely dependent on the technology itself, for example, the cost of the carbon abatement it can deliver. A technology's desirability is instead a function of its impact on a set of environmental and human systems, their trade-offs, and, crucially, the condition of the specific systems within which it is to be deployed. Water intensive technologies are less desirable in water stressed regions compared to areas with high water abundance. The RAF, as the SoS measure of aggregated impacts adopted here, reflects four relevant criteria and provides a quantification of relative desirability given resource availabilities and does not take feasibility constraints into account.

Here, we showed that no single technology was strictly dominant under either the equal weights RAF assessment or for any particular MS. We also showed how technology desirability varies across criteria combinations and across MSs given their local resource conditions. Two high-level conclusions can be drawn from this. Firstly, a diversified portfolio of technologies will be best suited to the nexus of environmental and human systems they are embedded in. Secondly, technology decision-making must include local concerns and not simply focus on a universal performance indicator or decision criterion such as cost or carbon footprint.

The results suggest that low-carbon technologies are generally more desirable to hydrocarbons. However, this is not to say that all renewable technologies are equally desirable in each MS. Our result illustrates nuclear to be highly desirable whilst biomass and large scale hydropower, two of the most popular renewable technologies around the world are shown to be highly undesirable across most countries of EU.

Around 20% of EU's renewable electricity is projected to come from biomass by 2020. According to our results not only this transition can put additional burden on water and land resources but it can also harshen land-use trade-offs with agriculture or other sectors. While nuclear was found to have the lowest RAF for almost all MSs, the negative public perception of this alternative due to the risks and security concerns associated with nuclear has led to its downward trajectory. Thus, it is important to also take other aspect such as the social issues into consideration in evaluating the overall performance of a technology. Geothermal, however, is showing low RAF across most MSs in the EU, and the increase in future share of this technology in portfolios would be a transition in the right direction, due to high desirability of this technology across the environmental and economic indicators considered.

While it is imperative to effectively address climate change, it is important not to lose sight of other environmental priorities. Without an understanding of how the energy sector decisions are linked to water management, land use and biodiversity, it is possible that impacts will be displaced from one area (climate) to another (water or land).

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