Titre: Title:	Investigating the role of surface engineering in mitigating greenhouse gas emissions of energy technologies: An outlook towards 2100
Auteurs: Authors:	Mohamad Kaddoura, Guillaume Majeau-Bettez, Ben Amor, Christian Moreau, & Manuele Margni
Date:	2022
Type:	Article de revue / Article
Référence: Citation:	Kaddoura, M., Majeau-Bettez, G., Amor, B., Moreau, C., & Margni, M. (2022). Investigating the role of surface engineering in mitigating greenhouse gas emissions of energy technologies: An outlook towards 2100. Sustainable Materials and Technologies, 32, e00425 (9 pages). https://doi.org/10.1016/j.susmat.2022.e00425

URL de PolyPublie: PolyPublie URL:	https://publications.polymtl.ca/10254/
Version:	Version finale avant publication / Accepted version Révisé par les pairs / Refereed
Conditions d'utilisation: Terms of Use:	CC BY-NC-ND

Titre de la revue: Journal Title:	Sustainable Materials and Technologies (vol. 32)
Maison d'édition: Publisher:	Elsevier B.V.
URL officiel: Official URL:	https://doi.org/10.1016/j.susmat.2022.e00425
Mention légale: Legal notice:	© 2022. This is the author's version of an article that appeared in Sustainable Materials and Technologies (vol. 32) . The final published version is available at https://doi.org/10.1016/j.susmat.2022.e00425. This manuscript version is made available under the CC-BY-NC-ND 4.0 license https://creativecommons.org/licenses/by-nc-nd/4.0/

Investigating the role of surface engineering in mitigating greenhouse gas emissions of energy technologies: An outlook towards 2100

Mohamad Kaddoura[a,*], Guillaume Majeau-Bettez[a,b], Ben Amor[c], Christian Moreau[d], Manuele Margni[a,e]
[a] CIRAIG, Department of Mathematics and Industrial Engineering, Polytechnique Montréal, C.P 6079, succ. Centre-Ville, Montréal, QC, H3C 3A7, Canada
[b] Industrial Ecology Program, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), E1-Høgskoleringen 5, Trondheim, 7491, Norway
[c] LIRIDE, Department of Civil and Building Engineering, Université de Sherbrooke, 2500 boul. De lUniversité, Sherbrooke, QC, J1K 2R1, Canada
[d] Department of Mechanical, Industrial and Aerospace Engineering, Concordia University, 1455 de Maisonneuve Blvd. W, Montréal, QC, H3G 1M8, Canada
[e] School of Engineering, University of Applied Sciences and Arts Western Switzerland (HES-SO), Sion, Switzerland

*Corresponding author, email: mohamad.kaddoura@polymtl.ca, address: CIRAIG, Polytechnique Montréal, P.O. Box 6079, succ. Centre-Ville, Montréal, QC, H3C 3A7, Canada.

Abstract (282 words)

Energy improvements in the energy sector constitute a key strategy to mitigate climate change. These expected improvements increasingly depend on the development of materials with improved surface characteristics. To prospectively assess the large-scale benefits and trade-offs of such novel surface engineering (SE) technology deployments in the energy sector, an integrated modelling framework is proposed. This paper links an integrated assessment model (IAM) forecasting socio-economic changes in energy supply with life cycle assessment (LCA) models of targeted technology candidates. Different shared socio-economic pathway narratives are used with the MESSAGE IAM to forecast future energy supply scenarios. A dynamic vintage model is employed to model plants decommissioning and adoption rates of innovative SE. Potential benefits and impacts of SE are assessed through prospective LCA. The approach is used to estimate the prospective GHG emission reduction potential achieved by large-scale adoption of innovative SE technologies to improve the efficiency of four energy conversion technologies (coal power plants, gas turbines, wind turbines and solar panels) until 2100. Applying innovative SE technologies to the energy sector has the potential of reducing annual CO2-eq emissions by 1.8 Gt in 2050 and 3.4 Gt in 2100 in an optimistic socio-economic pathway scenario. This corresponds to 7% and 8.5% annual reduction in the energy sector in 2050 and 2100, respectively. The mitigation potential of applying innovative SE technologies highly depends on the energy technology, the socio-economic pathways, and the implementation of stringent GHG mitigation policies. Due to their high carbon intensity, fossil-based technologies showed a higher GHG mitigation potential compared to renewables. Besides, GHG emissions related to the SE processes are largely offset by the GHG savings of the energy conversion technologies where the innovative SE technologies are applied.

Keywords: energy systems; efficiency improvement; integrated assessment models; thermal barrier coating; hydrophobic coating

1 Introduction

Electricity and heat production was the largest contributing sector (37%) to fossil CO_2 emissions in 2018 [1]. This sector is expected to remain pivotal for climate change mitigation, where the energy demand is expected to increase by 1.3% each year until 2040 under business-as-usual scenarios [2]. Although the use of some technologies (e.g., carbon capture and storage and renewable energy sources) to supply the increased demand provides a good potential in reducing greenhouse gas (GHG) emissions [3,4], a portfolio of different mitigation options is needed to solve the climate problem [5]. Improving the technical efficiency of energy technologies is a key mitigation strategy in any portfolio [6–8] where emission mitigation and decoupling policies should focus on improving the energy efficiency [9]. This justifies the European Union target of achieving a 36% energy efficiency improvement in 2030 compared to 1990, which will contribute to reaching their goal of a 55% reduction of GHG emissions [10]. Such efficiency gains will largely depend on improved surface properties. The use of surface engineering (SE) technologies thus has the potential of improving the energy efficiency in the energy sector, but surprisingly its potential role is still not widely studied in literature.

Surface engineering "encompasses all of those techniques and processes which are utilized to induce, modify, and enhance the performance – such as wear, fatigue and corrosion resistance and biocompatibility – of surfaces" [11]. Surface engineering technologies usually result in an increase in the component lifetime (e.g., by wear protection) [12] or a reduced energy demand in the use phase (e.g., by friction reduction) [13]. In the energy sector, surface engineering technologies could be used to further improve the efficiency of coal power plants [14], gas turbines [15], solar panels [16] and wind turbines [17]. In other energy conversion technologies, SE is mainly used to extend the lifetime of some components. Corrosion resistance coatings for critical components in biomass and waste-to-energy facilities have been recently developed to extend plant lifetimes [18]. In hydroelectric power plants, novel coating materials resist abrasive erosion and extend the lifespan of hydro turbines [19]. For nuclear power applications, the coating is usually used for the fuel storage (either new or used) to protect from corrosion. A zirconium alloy is used as fuel cladding to prevent radioactive fuel from dissipating into the coolant [20] and copper coatings are developed as corrosion barriers for used fuel nuclear containers [21]. When assessing the benefits of different coatings, it is necessary to investigate their performance under harsh conditions. For example, the reliability of thermal barrier coatings (TBCs) in gas turbine blade during erosion [22] and the durability of icephobic coatings during deicing cycles [23] could mean that recoating is necessary. Although the literature in the surface engineering domain is rich from a material-science point of view, "no holistic life cycle engineering approach can be found for the specific requirements of surface engineering" to study their environmental impacts [13].

While SE technologies provide efficiency improvements leading to lower GHG emissions in the use phase, they also incur some emissions during the production of coating materials and the coating process. To ensure that there is no shift of burden between different life cycle phases, a holistic perspective, such as life cycle assessment (LCA), should be used [24]. Various LCA studies examined individual SE technologies, mostly focusing on the impacts of the coating process in SE [25–28], while only few included the potential benefits in terms of reduced emissions during the use phase [29,30]. All these studies are of retrospective nature, whereas SE technologies are evolving and prospective LCAs are thus needed to anticipate and guide future technical developments. In a prospective LCA of an emerging technology, different technology alternatives should be analyzed and scenarios should be included [31]. Cooper and Gutowski [32] go further and propose including the market size of the new technology now and in the future, in addition to its diffusion and displacement rates, to extend the explorative analysis of anticipatory LCAs, which is currently missing in most studies.

To bring this large-scale, prospective dimension to LCA methodology, complementary tools are needed. Integrated Assessment Models (IAMs) provide future market sizes of energy conversion technologies based on consistent socio-economic pathways, filling this gap [33]. IAMs are numerical models that center on studying different pathways and scenarios for human and earth systems involving technology shifts and disruptions within the context of climate change and energy optimization [34]. The scenarios supply "descriptions of the future industrial system, such as the electricity mix, as input data to industrial ecology models for prospective assessment of specific emissions mitigation strategies not considered in IAMs" [35]. IAMs are usually linked to LCA to analyze the impact of evolving electricity mix supply in the future on specific technologies, e.g., comparing internal combustion engine vehicles with electric vehicles [36] and alternative aluminum production [37]. LCA is also linked to IAMs to account for possible shifts of impacts between different environmental categories in the energy sector, by including additional categories to GHG emissions [38–41]. The scenarios are driven by narratives describing different socio-economic pathways. The shared socio-economic pathways (SSPs) are commonly used narratives, where they are defined based on challenges for mitigation and for adaptation [42].

The aim of this paper is to quantify the environmental benefits and trade-offs of large-scale adoption of innovative surface engineering technologies to improve the energy conversion efficiency in the energy sector under different prospective socio-economic and policy scenarios. In other words, this article explores the share of expected energy efficiencies that hinges on the successful development and deployment of innovative SE technologies. The anticipated environmental performances are assessed in terms of potential impacts on the climate, on ecosystem quality, and on human health to identify potential burden shifting. The term "innovative" refers to traditional or new technologies that are not currently used in the energy sector, or technologies that are currently used but with new coating materials. The energy conversion technologies studied are coal power plants, gas turbines, solar panels and wind turbines. Due to the high uncertainty in the amount of lifetime extension achieved due to corrosion/erosion resistance in other energy conversion technologies, such applications are out of the scope of the study.

2 Material and methods

In this study, we develop an approach to quantify the benefits and potential trade-offs of surface engineering in three main steps (Figure 1). The following section proceeds by explaining each step: (2.1) identifying and documenting innovative surface engineering technologies and the efficiency gains that they enable, (2.2) developing sector-specific scenarios to scale up these gains, and (2.3) assessing the potential environmental benefits and impacts of these deployment scenarios.

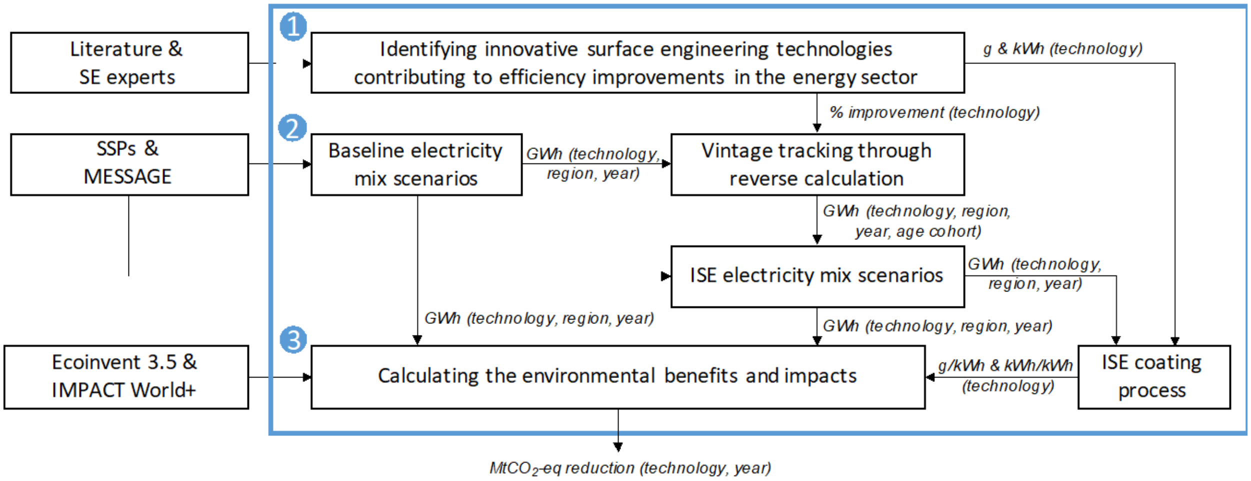

Figure 1 Overview of the methodology used to identify the mitigation potential of surface engineering technologies in the energy generation sector. ISE: innovative surface engineering, SSP: Shared socio-economic pathway, g: grams, kWh: kilowatt hour, GWH: gigawatt hour

2.1 Identifying innovative surface engineering technologies in the energy sector

This section gives an overview of the chosen innovative surface engineering technologies used to improve energy conversion efficiency in coal power plants, gas turbines, solar panels and wind turbines, where the current surface engineering research on energy technologies takes places.

Corrosion resistant coatings for ultra-supercritical coal power plants

Thermal power plants are described based on the conditions (pressure and temperature) where the electricity is generated. Plants operating below 538°C are termed subcritical, between 538°C and 565°C are supercritical, and above 565°C are ultra-supercritical, each with different efficiencies [43]. When operating at high temperatures, corrosion in the boiler is an issue and advanced materials or coatings are thus needed. In traditional coal power plants, 50/50 nickel chromium alloys are usually flame sprayed on boiler walls. Chromium oxidizes to Cr_2O_3 when alloyed with nickel, providing high temperature oxidation protection [14]. In ultra-supercritical conditions, higher hardness is required, thus other alloying elements should be used with nickel and chromium. Thermally sprayed NiCrBSi provides the desired properties and is currently used to protect against wear, abrasion, erosion and corrosion in various industrial applications (ibid.). Accordingly, we model NiCrBSi as the coating material to achieve efficiency improvements from ultra-supercritical power plants. We make the conservative assumption that current coal power plants are supercritical, as is typically the case in China, the country with the highest coal power plant capacity [44]. Supercritical plants have an efficiency of around 37% and ultra-supercritical 45% [45], which corresponds to an energy improvement of 22%. Therefore, in subsequent steps (Section 2.2), we will consider that a 22% improvement gain in ultra-supercritical coal power plants depends on innovative SE technology deployment. This parameter is varied between 10% and 30% to see the sensitivity of the results with respect to it.

New thermal barrier coatings for gas turbines

Thermal barrier coatings (TBCs) are ceramic coatings applied to the surfaces of metallic parts (superalloys) in the hottest part of gas turbine engines, allowing for operation at higher gas temperatures [15]. The efficiency of gas turbines can be approximated by the Carnot efficiency (Equation 1) multiplied by a Carnot factor of 0.75 [46]. The efficiency is thus directly proportional to the inlet gas temperature entering the turbine section (T_{high} in Equation 1), and reaching a higher temperature leads to an increase in the efficiency, assuming that we increase the pressure ratio as well [47]. Traditionally, 7 wt% yttria stabilized zirconia (YSZ) is the most commonly used TBC material due to its unique properties (low thermal conductivity and high thermal expansion); however, its applications are limited to 1200°C. The search of new coating materials applicable at temperatures above 1300°C is ongoing [48]. Coating materials with pyrochlores structure $A_2B_2O_7$ have lower thermal conductivity than YSZ and provide excellent thermal stability. In terms of thermal conductivity, $La_2Zr_2O_7$ (LZ) is the most promising replacement for YSZ; however, its low thermal expansion coefficient leads to higher thermal stress. Thus, $Gd_2Zr_2O_7$ (GZ) is more compatible in terms of thermal expansion and offers a good compromise [48] allowing to reach a temperature of 1400°C [49,50]. To estimate the improved efficiency of gas turbines using GZ, the efficiency was calculated based on Equation 1 and multiplied by the Carnot factor.

$$Carnot\ efficiency = 1 - \frac{T_{low}}{T_{high}}\ (Equation\ 1)$$

Where: T_{low}: Lowest temperature in the cycle; the inlet of the compressor (in Kelvin)

T_{high}: Turbine inlet temperature (in Kelvin)

The efficiency of combined cycle gas turbines with YSZ as a TBC is around 60% [51], with a T_{high} of 1473 K, and a T_{low} close to ambient temperature (287 K). When using GZ as a TBC, T_{high} increases to 1673 K, while the ambient temperature stays the same. Based on Equation 1 multiplied by the Carnot factor, the efficiency would increase from 60% to 62% (an improvement of 3.5%) when shifting to GZ as a TBC. Consequently, we will model a 3.5% improvement gain from SE technology deployment in the innovative gas turbines in the subsequent steps. This parameter is subject to temperatures achieved, and thus is varied between 1.5% and 4%, corresponding to temperatures of 1300°C and 1500°C, respectively to see the sensitivity of the results with respect to it.

Hydrophobic coating for solar panels (self-cleaning)

Hydrophobicity is a characteristic of the surface with superior water-repellent properties and is usually quantified by the water contact angle (CA) and the sliding angle (SA). Surfaces with a CA>90° are termed hydrophobic and those with a CA>150° and SA<10° are termed superhydrophobic [52]. Using hydrophobic coatings could achieve self-cleaning properties for surfaces by removing the dirt on the surface through rolling droplets of water on it. Solar photovoltaic panels can benefit from this property to improve their efficiency. Alamri et al. [16] found that solar panels coated with hydrophobic SiO_2 nanomaterial had an improved efficiency of 5% compared to manually cleaned uncoated ones, and 15% compared to dusty panels with no cleaning. In our study, we used the average value of 10% to model the efficiency improvement when the panels are coated, and the extremes are used in the sensitivity analysis.

Icephobic and superhydrophobic coatings for wind turbines

Icephobic coatings can be used on surfaces to repel water droplets, delay ice nucleation and reduce ice adhesion, which is beneficial in wind turbines situated in cold regions because of passive anti-icing [53]. Poly(tetrafluoroethylene) (PTFE) has been identified as a candidate icephobic coating for wind turbines, providing a contact angle of 145^{o} and slipping angle of 45^{o} [54]. The durability and practicality of applying icephobic coatings has been a limiting factor of implementing them [23], and accordingly we will use a superhydrophobic coating in our model. Superhydrophobicity, although not necessarily linked to icephobicity (ibid.), can be used in anti-icing applications. Polyvinylidene fluoride (PVDF) was the only superhydrophobic coating tested as a candidate anti-icing coating for wind turbines [55], achieving a contact angle of 156^{o}. The absence of data linking CA and SA to the amount of electric energy that can be saved by coating forces us to test the range provided in literature. Power losses due to ice accretion on the blades of wind turbines ranges between 0.005-50% [17]. In this study, we will model the improvement in generation efficiency with the average of 25% by using PVDF superhydrophobic coating in northern climates, and this parameter will be varied between 0.005% and 50% in the sensitivity analysis.

Table 1 summarizes the energy efficiency improvements that depend on innovative surface engineering technologies for different energy conversion technologies. Due to the uncertainty of the relative efficiency improvement values, a sensitivity analysis is also performed (Supporting Information, SI1, Figure S6) for the range provided between parentheses.

Table 1 Efficiency improvements from applying innovative surface engineering technologies to different energy conversion technologies. The range in the parentheses is used in the sensitivity analysis. NiCrBSi: nickel chrome boron silicium; GZ: gadolinium zirconate; SiO_2: silicon dioxide; PVDF: polyvinylidene fluoride

Energy conversion technology	**SE technology**	**Coating material**	**Relative improvement in energy conversion attributed to SE**
Coal power plants	Thermal spray	NiCrBSi	22% (10-30%)
Gas turbines	Thermal spray	GZ	3.5% (1.5-4%)
Solar panels	Sol gel	SiO_2	10% (5-10%)
Wind turbines	paint	PVDF	25% (0.005%-50%)

2.2 Energy generation scenarios

Baseline electricity mix scenarios

Having identified the efficiency improvements from SE for each technology, the next step is applying this improvement on a large scale based on scenarios of evolution of the electricity mix. Prospective energy scenarios until 2100, in terms of the total amount of energy supplied from each energy conversion technology, were obtained from the MESSAGE integrated assessment model [34], which includes 43 energy conversion technologies in 11 world regions and is available in open access. It operates in ten-year time steps between 2010 and 2100. MESSAGE was used with three baseline shared socio-economic scenarios [42] representing the two extreme scenarios (SSP1: "sustainability" and SSP3: "regional rivalry") with the moderate one (SSP2: "middle of the road"). In addition to the baseline scenarios, policy scenarios are also included, which contain additional constraints to reach certain radiative forcing. In this study, the representative concentration pathways (RCPs) associated with policy scenarios limiting the temperature increase to 1.5 degrees and 2 degrees were included. In the policy scenarios, technologies with carbon capture and storage (CCS) are also available.

Vintage tracking through reverse calculation

In our model, innovative SE technologies are adopted mainly by newly built power plants, thus it is important to anticipate both the replacement of decommissioned plants and the expansions in the installed capacity that are implied by the different energy scenarios. In absence of information about the age-cohort of the energy infrastructure in different SSPs over different years, we estimated these constructions with a stock-driven model, thereby estimating the in-use stock (in our case, the energy capacity satisfying a specific demand) as suggested by Pauliuk et al. [56]. Assuming that gas turbines, wind turbines and solar panels have a fixed lifetime of 30 years and coal power plants 40 years [57,58], the entire age-cohort would be decommissioned after 30 and 40 years, respectively. The model was run between the years 2020 and 2100, with a step of 10 years between each time series. In the outcomes of the MESSAGE model, no data is provided about the age-cohort of the energy infrastructure at t_0-1 (the year 2010 in our case). Accordingly, a normal distribution with a mean μ = 20 years old and a standard deviation σ = 10 years was taken to allocate the total energy capacity satisfying the demand into three age groups: 10, 20 and 30 years remaining. For coal power plants, with a lifetime of 40 years, μ was set to 25 years, and an additional age group of 40 years remaining is added. In the age-cohort table, this means that the capacity needed to supply the demand at t_0-1 was installed in the years 1990, 2000, and 2010 respectively (and 1980 for the coal power plants). For the coming years, a recursive procedure is repeated to fill the age-cohort; as the plants age (decommissioned), new ones are built to satisfy the increased demand. In some cases, the added capacity could be negative when the demand sharply reduces for some energy conversion technologies, so it is set to 0 instead (i.e., no new capacity is added that year), and the negative capacity is added to the age-cohort of the oldest technology, indicating early decommissioning of older plants. More about the vintage tracking could be found in the Supporting Information (SI1).

Penetration of innovative surface engineering technologies in the energy sector

After identifying the vintage of the power plants, we modelled the penetration of SE enhanced coal power plants, gas turbines, solar panels and wind turbines building on three scenarios as per Table 2., consistent with the narratives given by the socio-economic pathways (SSPs) [42]. For SSP1, the technology development and transfer are *rapid*, and the shift of energy conversion technologies is "directed away from fossil fuels, towards *efficiency* and renewables." In SSP2, the technology development is *medium* and *uneven*, the technology transfer is *slow*, and the change of energy conversion technologies has "some investment in renewables but continued reliance on fossil fuels." SSP3 has *slow* technology development and transfer, and a "*slow technology change*, directed toward domestic energy sources." In SSP1, retrofitting old plants by de-coating them and applying the new coating is assumed possible. In fact, gas turbine blades can be de-coated and recoated with minimum disruptions [59]. Besides, geographical constraints apply to the wind turbines, where innovative SE is used in northern countries where icing on the turbines increases downtimes in winter. In OECD, the proportion of wind turbines in cold climates is proxied by Canada and Sweden, the two cold regions with the highest capacities of wind turbines (6% of the OECD supply) [60]. In the reforming economies (e.g., Russia, Ukraine and Kazakhstan), all countries have subzero temperatures in the winter, and thus assumed to be cold climates. Accordingly, innovative SE is applied to all the energy supply in the reforming economies (REF)and 6% of the supply in the OECD. It is also assumed that 50% of the supplied energy from wind turbines occur in the winter.

Table 2 Linking the three assessed surface engineering deployment scenarios with the corresponding shared socio-economic pathway (SSP)

SE scenario	Corresponding SSP	Description
Pessimistic	SSP3	Innovative surface engineering technologies are applied only to 10% of newly deployed energy technologies.
Optimistic	SSP2	Innovative surface engineering technologies are applied to 80% of newly deployed energy technologies
Optimistic + Retrofit	SSP1	Innovative surface engineering technologies are applied to 100% of newly deployed energy technologies, with the possibility of applying them directly to 50% of in-stock technologies.

2.3 Environmental impacts

Having determined the rate of adoption of each energy conversion technology and the size of their market uptake (Section 2.2), we then turn to quantify the environmental consequences of this adoption. For that, a life cycle perspective is adopted to evaluate the environmental burdens and benefits of identified SE technologies. The potential burdens arise from the coating material and surface engineering processes, whereas the benefits are realized from the improved efficiency of energy conversion technologies as identified in Table 1. The inventory data for different coating techniques builds on proxy studies found in literature and documented in the Supporting Information (SI1, Tables S1-S6). The inventory data of each energy conversion technology is based on the energy outputs of different scenarios in the IAM obtained from the model described in the previous section.

The IAM provides the inventory of direct emissions associated with each energy conversion technology, but indirect emissions associated with other life cycle stages (e.g., mining and manufacturing) are not provided. Accordingly, emissions provided by the IAM are not used to quantify the environmental impacts. To include all the emissions and their related potential impacts, the impact factors for each technology (kgCO_2-eq/kWh) are calculated using ecoinvent

3.5 [61] and characterized with the "climate change, short term" midpoint indicator provided by IMPACTWorld+ (Default Recommended Midpoint 1.29) [62] and corresponding to the Global Warming Potential with 100-year time horizon. To account for a possible shift of impacts between different environmental categories, the areas of protection "ecosystem quality" and "human health" (both excluding the "climate change" endpoint results) were also calculated based on IMPACTWorld+ (Default Recommended Damage 1.47). The characterization factors for the energy supplied by power plants with a vintage adopting innovative surface engineering were reduced proportional to the energy efficiency gains (Table 1). To be consistent, the same database and impact assessment methods were used to calculate the impact of the coating process.

Our model also differentiates between the five geographical regions in the SSPs by proxying them to the country in that region with the highest production volume of an energy conversion technology in ecoinvent. The mapping of different technologies in MESSAGE with their equivalent flows in ecoinvent is available in the Supporting Information (SI1, Table S8). Since the data for carbon capture and storage (CCS) is not available in ecoinvent, it is assumed that the climate change potential is 75% less impactful for coal power plants, 55% less impactful for gas turbines and -10 times less impactful for biomass power plants [58]. For the ecosystem quality and human health indicators, CCS technologies have a larger impact (ibid.), and the scaling factors used are provided in the Supporting Information (SI2).

The python code for our model, COATS (CO_2 Abatement Tied to Surface engineering), can be found here: https://github.com/mohamadkaddoura/COATSResults.

3 Results

3.1 Future energy supply

Figure 2 shows the energy supplied with SE-enhanced technologies replacing the one supplied with the baseline technology for the different SSPs. Energy supplied in absolute units (EJ) is provided on the y-axis on the left and in percentage with respect to the total energy supply on the right. The reference year is 2020, where 0% of the current energy conversion technologies operate with the innovative SE technologies. Results depend on the share of each energy conversion technology in the original SSPs, the age-cohort of those technologies and the adoption rates of innovative SE technologies according to the narratives described in Table 2.

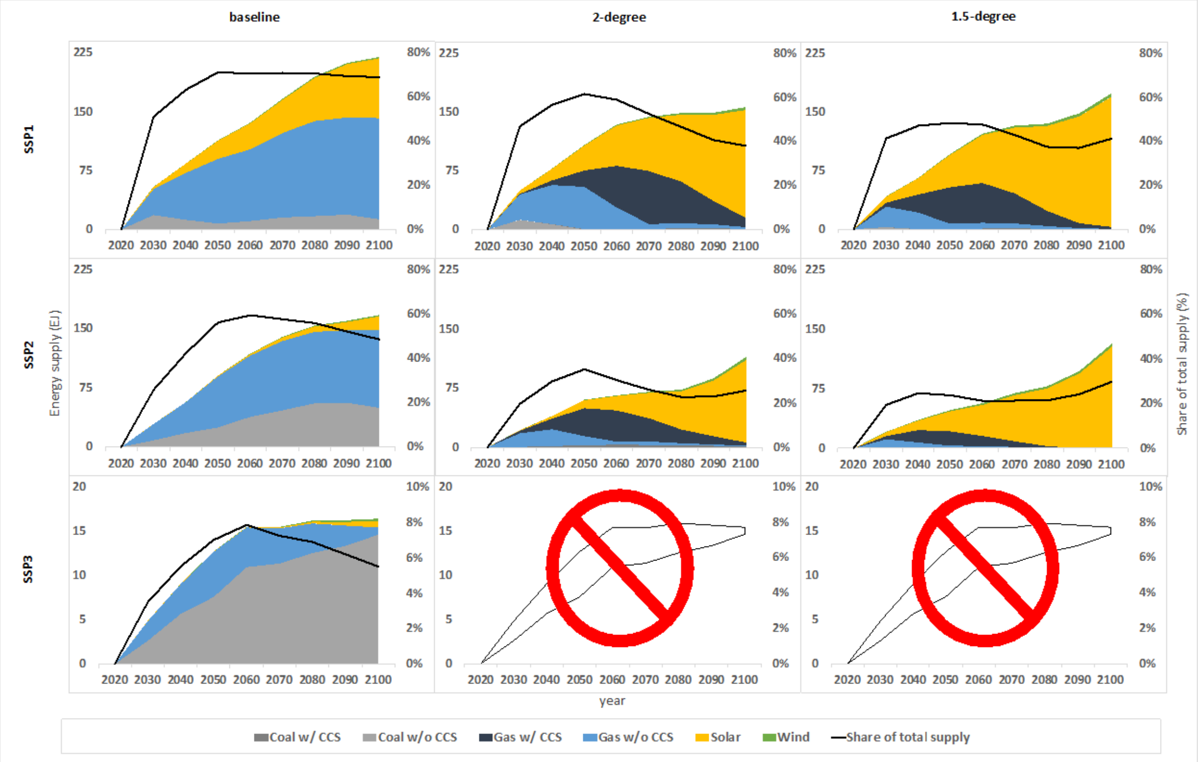

Figure 2 Energy supplied from innovative SE-enhanced energy conversion technologies replacing baseline ones for SSP1, SSP2, and SSP3 from 2020 to 2100 including the baseline scenario and the 1.5-degree and 2-degree policy scenarios. The left axis represents the energy supply replaced by innovative SE-enhanced energy conversion technologies (in EJ), and the right axis represents the share of the energy supplied by SE-enhanced technologies with respect to the total energy supply.

Thanks to the high adoption rates in SSP1, innovative SE would be applied to around 50% of the energy technologies in 2030 and saturating at around 70% by 2050 in the baseline scenario. Energy supplied by SE-enhanced gas turbines is the highest because most of the energy is supplied by gas turbines in the baseline SSP1, and SE is applied to 100% of the new plants. By the year 2100, energy supplied by the SE-enhanced wind turbines and solar panels represents a share that is almost half of that of gas turbines, while the share supplied by SE-enhanced coal power plants is negligible. In the policy scenarios of SSP1, more renewables are introduced, and CCS technologies become available. Solar panels become the dominant technology adopting SE, while the total share of technologies adopting innovative SE decreases to around 45% in 2100, because nuclear power plants (around 20% in 2100) are forecasted to replace coal power plants and gas turbines, and SE is not applied to increase the efficiency of nuclear power plants in our model.

In SSP2 and SSP3 baseline scenarios, the share of energy supplied by SE-enhanced technologies steadily increases from 2020 to 2060 reaching 60% and 8%, respectively. After 2060, the year where all the energy conversion technologies in the age-cohort are "new" compared to the base year 2020, the energy supplied by newly deployed coal, gas, solar and wind plants will decrease relative to an increase of the energy supplied by other technologies where innovative SE is not applied (i.e., biomass, hydro and nuclear). Similar to SSP1, SE technologies are mostly applied to gas turbines in SSP2. However, more energy is supplied by SE-enhanced coal power plants and solar panels have a lower share. In SSP3, SE technologies are mostly applied to coal power plants, but in absolute values, the energy supplied by SE-enhanced coal power plants is lower than that in SSP1 (except for the year 2100) due to the lower adoption rates in SSP3. The policy scenarios for SSP2 follow the same trend as SSP1 (SE mainly applied to solar panels), whereas the policy scenarios can't be reached in SSP3 due to socio-economic conditions.

3.2 Environmental impacts

The climate change potential impact of each SSP scenario with and without SE is shown in Figure 3. The cumulative benefits (in terms of GHG mitigation) are represented by the area between the solid lines (where SE is not applied) and the dashed lines (where SE is applied) for each SSP scenario. For all the scenarios, the benefits are mainly from coal power plants, and to a lower extent, gas turbines.

In the baseline scenarios that exclude introduction of energy policies (the red, blue and light green curves), the lowest benefits are achieved in SSP3 (narrative with low adoption rates of the SE technologies). The greatest benefits are observed in SSP2, because although it has a lower adoption rate of SE than SSP1, it includes more coal power plants, where the improvements from SE are most realized. In SSP2, an annual reduction of 1.8 Gt CO2-eq is forecasted by 2050 and 3.4 Gt CO2-eq by 2100, corresponding to a 7% and 8.5% reduction of GHG emissions from the energy sector, respectively. An annual reduction of 1 Gt CO2-eq and 1.7 Gt CO2-eq is forecasted for SSP1 baseline scenario by 2050 and 2100, respectively, representing a 6% reduction of GHG emissions. Lower reductions are achieved in both SSP1 and SSP2 policy scenarios because the climate change impacts are already lower relative to their respective baselines, and they include more renewables, which achieve less benefits from innovative SE technologies. Beyond GHG emissions, a net reduction is also achieved for ecosystem quality and human health (Figures S3 and S4 in the Supporting Information SI1).

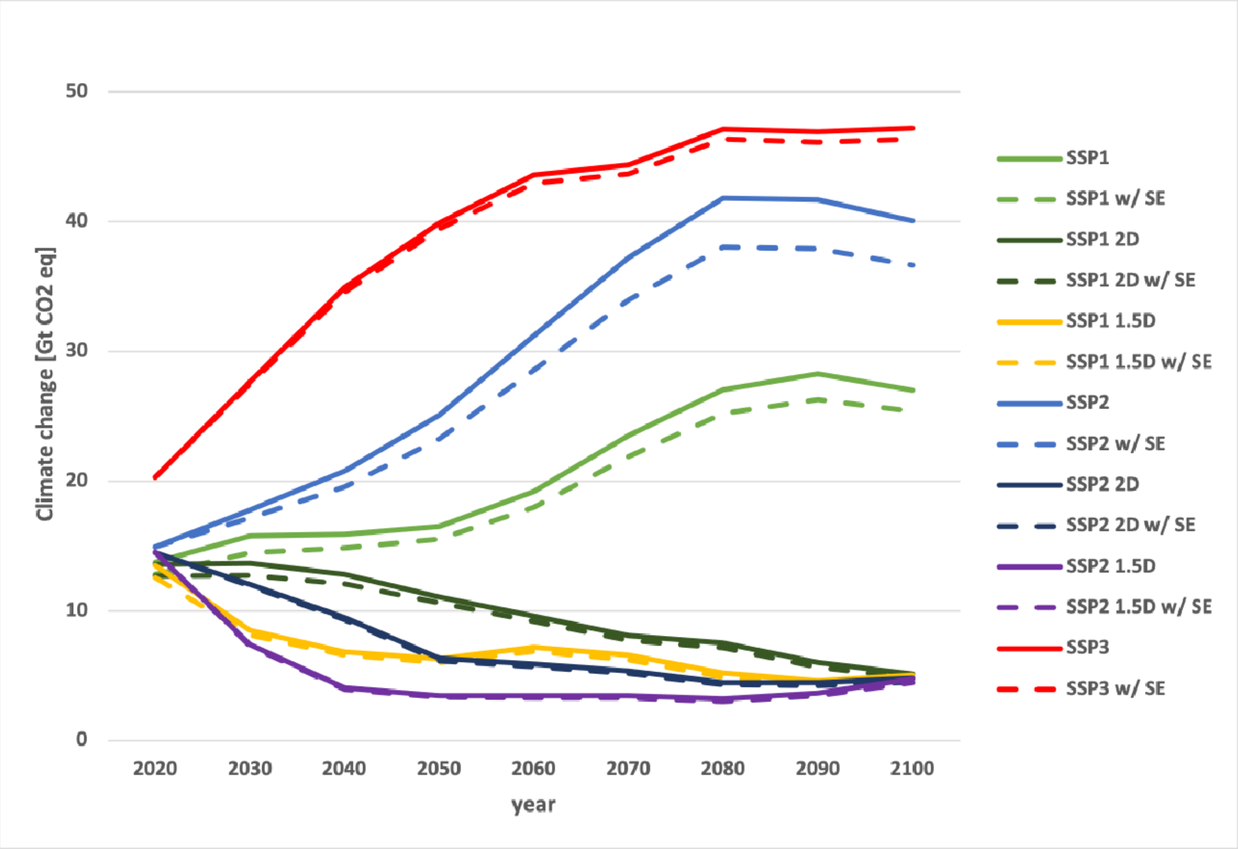

Figure 3 Prospective climate change potential impact from global electricity production based on different shared socio-economic pathways (SSPs) with (dashed lines) and without (solid lines) innovative surface engineering technologies. The red, blue and light green curves represent the baseline scenarios where no energy policies are introduced, and the 1.5D and 2D are policy mitigation scenarios corresponding to the 1.5 degree and 2 degree rising temperature targets in the Paris Agreement, respectively.

The climate change potential impacts from the coating process (including the production of the coating materials and other indirect upstream processes) are low compared to the benefits of the SE-enhanced energy conversion efficiency, and a net GHG reduction is always achieved (Figure 4). The impacts of the coating process are mainly from the production of NiCrBSi used in thermal spraying the boiler of the coal power plants. The same is true for the impacts on ecosystem quality and human health (Supporting Information SI1).

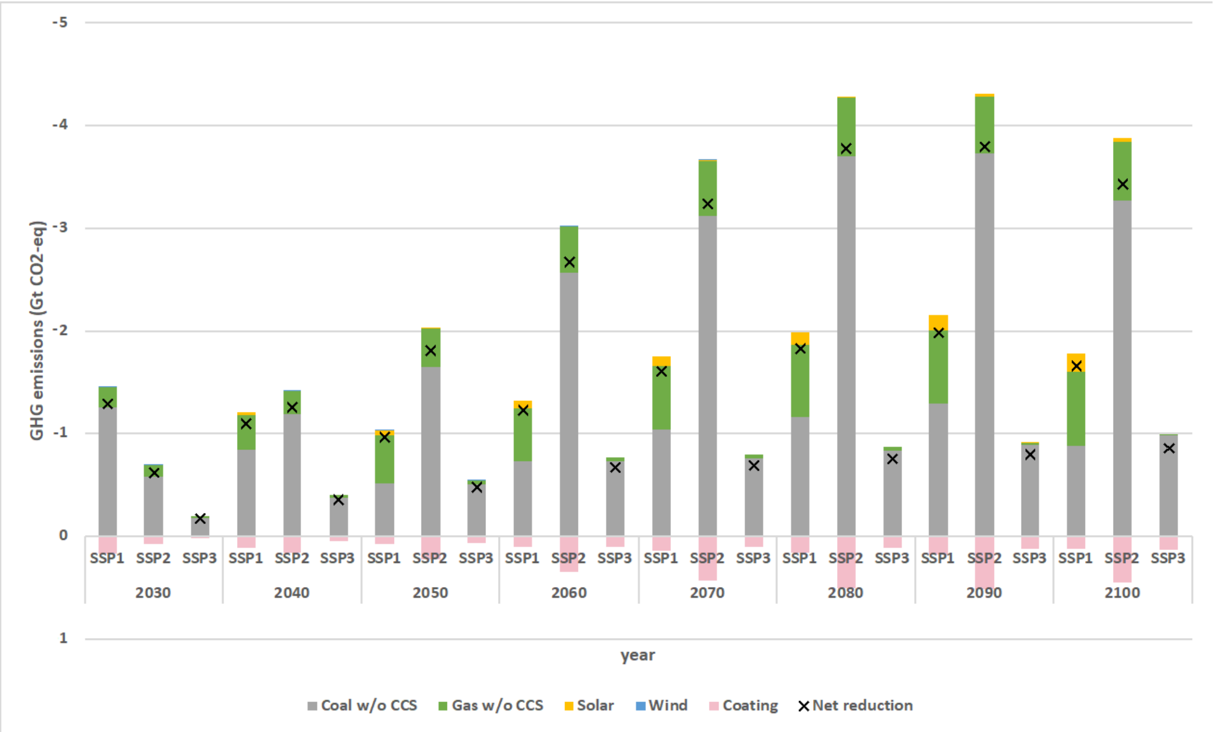

Figure 4 The contribution of surface engineering technologies on different energy production technologies to reducing CO2-eq emissions in different SSPs from 2030 to 2100.

The magnitude of environmental benefits is explained by three main factors: the share of energy supplied by each energy conversion technology (Figure 2), the efficiency improvement (Table 1) and the emission intensity of each technology without SE (kgCO$_2$-eq/kWh). For example, although for wind turbines the gain in energy efficiency is 25% compared to 5% in gas turbines, the emission from the former without SE is 14-25 gCO$_2$-eq/kWh vs. 550-1,000 gCO$_2$-eq/kWh for the latter. This corresponds to a reduction of 4-6 gCO$_2$-eq/kWh for wind turbines and 25-50 gCO$_2$-eq/kWh for gas turbines. This also explains the important contribution of SE in coal power plants in GHG reduction due to the scale of the initial emissions. Despite representing a low share of the overall energy supply in SSP1 and SSP2 (Figure 3), coal power plants gain significantly in energy efficiency (22%) when SE is applied, coupled with high emissions without SE (around 1,000gCO$_2$-eq/kWh).

4 Discussion and Conclusions

4.1 Linking IAMs and LCA

This work illustrated how linking IAMs and LCA provides helpful insights about prospective environmental studies on large-scale adoption of novel technologies. The IAM forecasts future energy demands based on consistent socio-economic scenarios and constraints needed in prospective environmental models [31,32]. LCA has been integrated to overcome two weaknesses of IAMs: (i) inclusion of the life cycle perspective of energy conversion technologies such as the infrastructure, being the key contributor to renewables and (ii) expanding the analysis of potential environmental impacts beyond the ones related to GHG emissions, such as ecosystem quality and human health. Besides, the LCA model of prospective SE processes includes the prospective life cycle inventory of the electricity supply obtained from our model.

This study contributes to a larger community effort to validate from the bottom-up (detailed engineering models) the feasibility and implications of macroscale scenarios (e.g., the ones in IAM) [35]. In this study, we point to the efficiency gains that hinge specifically on the progress of SE technologies, and how would they affect the global emissions provided by energy technologies in IAMs. This approach can be generalized so as to detail the physical and value-chain transformations necessary to enable the overall climate change mitigation effort and assess the likelihood of energy efficiency objectives in reaching a specific mitigation level.

4.2 Potential of SE in mitigating climate change

Surface engineering technologies have the potential of reducing GHG emissions in the energy sector by improving the energy efficiency. The reduced emissions come mainly from fossil-based technologies (coal power plants and gas turbines) because gains in energy efficiency are linked with reduction in fossil fuel consumption and thus high intensity GHG emissions. Similar or higher efficiency gains in renewable energy conversion technologies have lower influence on GHG mitigation, with such technologies having much lower GHG emission intensities compared to fossil fuels. Despite lower GHG mitigation potential for wind turbines and solar panels, the impact of the coating process remains smaller than the environmental benefits over the life cycle. Thus, such an efficiency gain may contribute to helping these technologies reach market profitability and not require as much subsidy needed today to achieve decarbonization scenarios.

In the best-case scenario (SSP2-baseline), SE can contribute to an annual reduction of 1.8 GtCO$_2$-eq by 2050, representing a 7% reduction in the total GHG emissions from the energy sector. This falls short from the required 19 GtCO$_2$-eq annual reduction (75% reduction) required in the policy scenario to achieve the two-degree temperature increase target in the policy scenario. Still, the magnitude of the reductions achieved is comparable to the potential of other mitigation measures. CCS technologies that were in trial operation in 2009 captured and stored 3 MtCO$_2$-eq from power plants and could contribute to a 20% reduction in world emissions from energy in the future [4]. This suggests that SE technology deployment is essential to a portfolio of highly relevant mitigation options to address the climate problem.

Another benefit of SE in the energy sector, which was not included in this study, is when it is used to increase the durability of components. SE could be used to extend the lifetime of energy conversion technologies and would contribute to reduced emissions from the avoided production of primary materials in the construction phase. For coal and gas power plants, the global warming potential of constructing the plants is 0.14% and 0.25% of the total impact, respectively [61,62]. Thus, extending the lifetime of the plants would have negligible benefits in term of GHG reduction compared to the potential gains in the operation phase. On the other hand, the impact of the infrastructure is around 100% of the total impact for solar panels and wind turbines (ibid.), and more benefits could be expected.

4.3 Limitations and future work

Despite its efficiency and simplicity in giving exploratory insights, it is important to take the approach proposed in this article with care, because it is subject to some uncertainties. The adoption rates of innovative SE technologies in energy conversion technologies for different SSPs were chosen to be compatible with the narratives of the SSPs. SSP3 is the most sensitive scenario to adoption rates, where a 4.8 $GtCO_2$-eq reduction between 2020 and 2100 could be achieved if the adoption rate increases by one percentage point (Supporting Information, SI1, Table S10). This could be improved in the future by looking into the maturity of the technologies and having a global parameter for technology developments in the SSPs. Besides, parameters used for vintage tracking through reverse calculation (e.g., the fixed age of the power plants and the initial normal distribution of the age-cohort) adds some uncertainties in the results. Providing a detailed energy outcome from IAMs, split by age-cohorts, would make linking more reliable. The same applies for the efficiency gains estimated from literature, where the efficiency gains are qualitatively mentioned, but rarely quantified. A sensitivity analysis indicated a net benefit in terms of GHG mitigation from the SE technologies beyond 1% gains in energy efficiency (Supporting Information, SI1, Figure S5).

In addition, improving the efficiency of energy conversion technologies might steer the supply from some technologies to others as they become cheaper, which was not assessed in our study. The IAM is not optimized after implementing the efficiency gains, due to the absence of the parameters used in the modelling. It is, however, assumed that the improvement in efficiencies does not affect the price elasticities and the equilibrium of the IAM. Although for coal power plants the improvement in efficiency is significant (22%), making it competitive in terms of price; it was assumed that countries will still phase out this technology due to energy policies. The effect on the equilibrium of the model could be tested in future studies if the price parameters used for modelling the SSPs are provided.

Finally, although the model shows a GHG emissions mitigation potential of up to 8.5% by adopting innovative SE technologies in the energy sector, these benefits might be partly offset by a risk of lowering the recyclability potential for surface engineered materials. The material cycles and recycling are ignored in most IAMs [35], which could be a limiting factor for adopting a new technology [32]. Despite the discussed uncertainties, linking IAM and LCA is sufficient for assessing prospective GHG mitigation scenarios in the energy sector.

Supplementary material

Supporting Information. SI1: Additional Information for the LCA and Additional Figures, SI2: Excel sheet with the model Input Data, SI3: Excel sheet with the model Output Data

CRediT authorship contribution statement

Mohamad Kaddoura: Conceptualization, Methodology, Formal analysis, Data Curation, Visualization, Writing – original draft. **Guillaume Majeau-Bettez:** Conceptualization, Methodology, Data Curation, Writing – review & editing, Supervision. **Ben Amor:**

Conceptualization, Methodology, Writing – review & editing, Supervision. **Christian Moreau**: Validation, Writing – review & editing, Funding acquisition. **Manuele Margni:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Acknowledgement

This work was funded by the Natural Sciences and Engineering Research Council (NSERC) of Canada through the Green Surface Engineering for Advanced Manufacturing (GreenSEAM) Strategic Network Grant.

References

[1] M. Crippa, G. Oreggioni, D. Guizzardi, M. Muntean, E. Schaaf, E. Lo Vullo, E. Solazzo, F. Monforti-Ferrario, J. Olivier, E. Vignati, Fossil CO2 & GHG emissions of all world countries: 2019 report, European Commision, Luxemborg, 2019. https://doi.org/10.2760/687800.

[2] IEA, World Energy Outlook 2019, (2019). https://www.iea.org/reports/world-energy-outlook-2019 (accessed January 2, 2020).

[3] N.L. Panwar, S.C. Kaushik, S. Kothari, Role of renewable energy sources in environmental protection: A review, Renew. Sustain. Energy Rev. 15 (2011) 1513–1524. https://doi.org/10.1016/j.rser.2010.11.037.

[4] R.S. Haszeldine, Carbon Capture and Storage: How Green Can Black Be?, Science (80-.). 325 (2009) 1647–1652. https://doi.org/10.1126/science.1172246.

[5] S. Pacala, R. Socolow, Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies, Science (80-.). 305 (2004) 968–972. https://doi.org/10.1126/science.1100103.

[6] D.S. Kwon, J.H. Cho, S.Y. Sohn, Comparison of technology efficiency for CO2 emissions reduction among European countries based on DEA with decomposed factors, J. Clean. Prod. 151 (2017) 109–120. https://doi.org/10.1016/j.jclepro.2017.03.065.

[7] E. Lanzi, E. Verdolini, I. Haščič, Efficiency-improving fossil fuel technologies for electricity generation: Data selection and trends, Energy Policy. 39 (2011) 7000–7014. https://doi.org/10.1016/j.enpol.2011.07.052.

[8] D. Guan, J. Meng, D.M. Reiner, N. Zhang, Y. Shan, Z. Mi, S. Shao, Z. Liu, Q. Zhang, S.J. Davis, Structural decline in China's CO2 emissions through transitions in industry and energy systems, Nat. Geosci. 11 (2018) 551–555. https://doi.org/10.1038/s41561-018-0161-1.

[9] Q. Wang, X. ting Jiang, S. Ge, R. Jiang, Is economic growth compatible with a reduction in CO2 emissions? Empirical analysis of the United States, Resour. Conserv. Recycl. 151 (2019) 104443. https://doi.org/10.1016/j.resconrec.2019.104443.

[10] EC, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our , (2020). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0562 (accessed January 1, 2020).

[11] K.N. Strafford, C. Subramanian, Surface engineering: An enabling technology for manufacturing industry, J. Mater. Process. Technol. 53 (1995) 393–403. https://doi.org/10.1016/0924-0136(95)01996-R.

[12] K. Nadolny, W. Kapłonek, M. Sutowska, P. Sutowski, P. Myśliński, A. Gilewicz, B. Warcholiński, Moving towards sustainable manufacturing by extending the tool life of the pine wood planing process using the AlCrBN coating, Sustain. Mater. Technol. 28 (2021). https://doi.org/10.1016/j.susmat.2021.e00259.

[13] A. Leiden, P. Brand, F. Cerdas, S. Thiede, C. Herrmann, Transferring life cycle engineering to surface engineering, 90 (2020) 557–562. https://doi.org/10.1016/j.procir.2020.02.132.

[14] V.H. Hidalgo, F.J.B. Varela, A.C. Menéndez, S.P. Martínez, A comparative study of high-

temperature erosion wear of plasma-sprayed NiCrBSiFe and WC-NiCrBSiFe coatings under simulated coal-fired boiler conditions, Tribol. Int. 34 (2001) 161–169. https://doi.org/10.1016/S0301-679X(00)00146-8.

[15] D.R. Clarke, M. Oechsner, N.P. Padture, Thermal-barrier coatings for more efficient gas-turbine engines, MRS Bull. 37 (2012) 891–898. https://doi.org/10.1557/mrs.2012.232.

[16] H.R. Alamri, H. Rezk, H. Abd-Elbary, H.A. Ziedan, A. Elnozahy, Experimental investigation to improve the energy effciency of solar PV panels using hydrophobic SiO2 nanomaterial, Coatings. 10 (2020). https://doi.org/10.3390/COATINGS10050503.

[17] O. Parent, A. Ilinca, Anti-icing and de-icing techniques for wind turbines: Critical review, Cold Reg. Sci. Technol. 65 (2011) 88–96. https://doi.org/10.1016/j.coldregions.2010.01.005.

[18] Y. Kawahara, An overview on corrosion-resistant coating technologies in biomass/waste-to-energy plants in recent decades, Coatings. 6 (2016). https://doi.org/10.3390/coatings6030034.

[19] S. Sangal, M.K. Singhal, R.P. Saini, Hydro-abrasive erosion in hydro turbines: a review, Int. J. Green Energy. 15 (2018) 232–253. https://doi.org/10.1080/15435075.2018.1431546.

[20] D. Jin, F. Yang, Z. Zou, L. Gu, X. Zhao, F. Guo, P. Xiao, A study of the zirconium alloy protection by Cr3C2-NiCr coating for nuclear reactor application, Surf. Coatings Technol. 287 (2016) 55–60. https://doi.org/10.1016/j.surfcoat.2015.12.088.

[21] P.G. Keech, P. Vo, S. Ramamurthy, J. Chen, R. Jacklin, D.W. Shoesmith, Design and development of copper coatings for long term storage of used nuclear fuel, Corros. Eng. Sci. Technol. 49 (2014) 425–430. https://doi.org/10.1179/1743278214Y.0000000206.

[22] Y.Q. Xiao, L. Yang, Y.C. Zhou, Y.G. Wei, N.G. Wang, Dominant parameters affecting the reliability of TBCs on a gas turbine blade during erosion by a particle-laden hot gas stream, Wear. 390–391 (2017) 166–175. https://doi.org/10.1016/j.wear.2017.07.013.

[23] Z.A. Janjua, B. Turnbull, K.L. Choy, C. Pandis, J. Liu, X. Hou, K.S. Choi, Performance and durability tests of smart icephobic coatings to reduce ice adhesion, Appl. Surf. Sci. 407 (2017) 555–564. https://doi.org/10.1016/j.apsusc.2017.02.206.

[24] ISO, ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework, (2006). https://www.iso.org/standard/37456.html (accessed March 15, 2020).

[25] N. Serres, F. Hlawka, S. Costil, C. Langlade, F. Machi, Microstructures and environmental assessment of metallic NiCrBSi coatings manufactured via hybrid plasma spray process, Surf. Coatings Technol. 205 (2010) 1039–1046. https://doi.org/10.1016/j.surfcoat.2010.03.048.

[26] S. Peng, T. Li, M. Li, Y. Guo, J. Shi, G.Z. Tan, H. Zhang, An integrated decision model of restoring technologies selection for engine remanufacturing practice, J. Clean. Prod. 206 (2019) 598–610. https://doi.org/10.1016/j.jclepro.2018.09.176.

[27] N. Serres, F. Hlawka, S. Costil, C. Langlade, F. MacHi, Corrosion properties of in situ laser remelted NiCrBSi coatings comparison with hard chromium coatings, J. Mater. Process. Technol. 211 (2011) 133–140. https://doi.org/10.1016/j.jmatprotec.2010.09.005.

[28] A. Moign, A. Vardelle, N.J. Themelis, J.G. Legoux, Life cycle assessment of using powder and liquid precursors in plasma spraying: The case of yttria-stabilized zirconia, Surf. Coatings Technol. 205 (2010) 668–673. https://doi.org/10.1016/j.surfcoat.2010.07.015.

[29] C. Bauer, J. Buchgeister, R. Hischier, W.R. Poganietz, L. Schebek, J. Warsen, Towards a framework for life cycle thinking in the assessment of nanotechnology, J. Clean. Prod. 16 (2008) 910–926. https://doi.org/10.1016/j.jclepro.2007.04.022.

[30] H. Wigger, M. Steinfeldt, A. Bianchin, Environmental benefits of coatings based on nano-tungsten-carbide cobalt ceramics, J. Clean. Prod. 148 (2017) 212–222. https://doi.org/10.1016/j.jclepro.2017.01.179.

[31] R. Arvidsson, A.M. Tillman, B.A. Sandén, M. Janssen, A. Nordelöf, D. Kushnir, S. Molander, Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA, J. Ind. Ecol. 22 (2018) 1286–1294. https://doi.org/10.1111/jiec.12690.

[32] D.R. Cooper, T.G. Gutowski, Prospective Environmental Analyses of Emerging Technology: A Critique, a Proposed Methodology, and a Case Study on Incremental Sheet Forming, J. Ind. Ecol. 24 (2020) 38–51. https://doi.org/10.1111/jiec.12748.

[33] L.R. Adrianto, M.K. van der Hulst, J.P. Tokaya, R. Arvidsson, C.F. Blanco, C. Caldeira, G. Guillén-Gonsálbez, S. Sala, B. Steubing, M. Buyle, M. Kaddoura, N.H. Navarre, J. Pedneault, M. Pizzol, B. Salieri, T. van Harmelen, M. Hauck, How can LCA include prospective elements to assess emerging technologies and system transitions? The 76th LCA Discussion Forum on Life Cycle Assessment, 19 November 2020, Int. J. Life Cycle Assess. 26 (2021) 1541–1544. https://doi.org/10.1007/s11367-021-01934-w.

[34] D. Huppmann, M. Gidden, O. Fricko, P. Kolp, C. Orthofer, M. Pimmer, N. Kushin, A. Vinca, A. Mastrucci, K. Riahi, V. Krey, The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development, Environ. Model. Softw. 112 (2019) 143–156. https://doi.org/10.1016/j.envsoft.2018.11.012.

[35] S. Pauliuk, A. Arvesen, K. Stadler, E.G. Hertwich, Industrial ecology in integrated assessment models, Nat. Clim. Chang. 7 (2017) 13–20. https://doi.org/10.1038/nclimate3148.

[36] A.M. Beltran, B. Cox, C. Mutel, D.P. Van Vuuren, When the Background Matters Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment, 24 (2018). https://doi.org/10.1111/jiec.12825.

[37] J. Pedneault, G. Majeau-Bettez, V. Krey, M. Margni, What future for primary aluminium production in a decarbonizing economy?, Glob. Environ. Chang. 69 (2021) 102316. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2021.102316.

[38] M. Pehl, A. Arvesen, F. Humpenöder, A. Popp, E.G. Hertwich, G. Luderer, Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling, Nat. Energy. 2 (2017) 939–945. https://doi.org/10.1038/s41560-017-0032-9.

[39] G. Luderer, M. Pehl, A. Arvesen, T. Gibon, B.L. Bodirsky, H.S. de Boer, O. Fricko, M. Hejazi, F. Humpenöder, G. Iyer, S. Mima, I. Mouratiadou, R.C. Pietzcker, A. Popp, M. van den Berg, D. van Vuuren, E.G. Hertwich, Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies, Nat. Commun. 10 (2019) 1–13. https://doi.org/10.1038/s41467-019-13067-8.

[40] M. Fernández Astudillo, K. Vaillancourt, P.O. Pineau, B. Amor, Human Health and Ecosystem Impacts of Deep Decarbonization of the Energy System, Environ. Sci. Technol. 53 (2019) 14054–14062. https://doi.org/10.1021/acs.est.9b04923.

[41] L. Vandepaer, E. Panos, C. Bauer, B. Amor, Energy System Pathways with Low Environmental Impacts and Limited Costs: Minimizing Climate Change Impacts Produces Environmental Cobenefits and Challenges in Toxicity and Metal Depletion Categories, Environ. Sci. Technol. 54 (2020) 5081–5092. https://doi.org/10.1021/acs.est.9b06484.

[42] B.C. O'Neill, E. Kriegler, K.L. Ebi, E. Kemp-Benedict, K. Riahi, D.S. Rothman, B.J. van Ruijven, D.P. van Vuuren, J. Birkmann, K. Kok, M. Levy, W. Solecki, The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, Glob. Environ. Chang. 42 (2017) 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004.

[43] R. Viswanathan, J.F. Henry, J. Tanzosh, G. Stanko, J. Shingledecker, B. Vitalis, R. Purgert, U.S. Program on materials technology for ultra-supercritical coal power plants, J. Mater. Eng. Perform. 14 (2005) 281–292. https://doi.org/10.1361/10599490524039.

[44] Q. Liu, M. Shi, K. Jiang, New power generation technology options under the greenhouse gases mitigation scenario in China, Energy Policy. 37 (2009) 2440–2449. https://doi.org/10.1016/j.enpol.2009.02.044.

[45] V. Prakash, S. Ghosh, K. Kanjilal, Costs of avoided carbon emission from thermal and renewable sources of power in India and policy implications, Energy. 200 (2020) 117522. https://doi.org/10.1016/j.energy.2020.117522.

[46] S.C. Gülen, Modern gas turbine combined cycle, Turbomach. Int. 54 (2013) 31–35.

[47] T. Wang, The gas and steam turbines and combined cycle in IGCC systems, Elsevier Ltd, 2017. https://doi.org/10.1016/B978-0-08-100167-7.00028-7.

[48] R. Vaßen, M.O. Jarligo, T. Steinke, D.E. Mack, D. Stöver, Overview on advanced thermal barrier coatings, Surf. Coatings Technol. 205 (2010) 938–942. https://doi.org/10.1016/j.surfcoat.2010.08.151.

[49] E. Bakan, D.E. Mack, G. Mauer, R. Vaßen, Gadolinium zirconate/YSZ thermal barrier coatings: Plasma spraying, microstructure, and thermal cycling behavior, J. Am. Ceram. Soc. 97 (2014) 4045–4051. https://doi.org/10.1111/jace.13204.

[50] S. Mahade, D. Zhou, N. Curry, N. Markocsan, P. Nylén, R. Vaßen, Tailored microstructures of gadolinium zirconate/YSZ multi-layered thermal barrier coatings produced by suspension plasma spray: Durability and erosion testing, J. Mater. Process. Technol. 264 (2019) 283–294. https://doi.org/10.1016/j.jmatprotec.2018.09.016.

[51] E. Moreno Ruiz, L. Valsasina, F. Brunner, A. Symeonidis, D. FitzGerald, K. Treyer, G. Bourgault, G. Wernet, Documentation of changes implemented in ecoinvent database v3.5. Ecoinvent, Zürich, Switzerland., 5 (2018) 1–97.

[52] D. Tejero-Martin, M. Rezvani Rad, A. McDonald, T. Hussain, Beyond Traditional Coatings: A Review on Thermal-Sprayed Functional and Smart Coatings, Springer US, 2019. https://doi.org/10.1007/s11666-019-00857-1.

[53] X. Huang, N. Tepylo, V. Pommier-Budinger, M. Budinger, E. Bonaccurso, P. Villedieu, L. Bennani, A survey of icephobic coatings and their potential use in a hybrid coating/active ice protection system for aerospace applications, Prog. Aerosp. Sci. 105 (2019) 74–97. https://doi.org/10.1016/j.paerosci.2019.01.002.

[54] R. Karmouch, S. Coudé, G. Abel, G.G. Ross, Icephobic PTFE coatings for wind turbines operating in cold climate conditions, 2009 IEEE Electr. Power Energy Conf. EPEC 2009. (2009) 0–5. https://doi.org/10.1109/EPEC.2009.5420897.

[55] C. Peng, S. Xing, Z. Yuan, J. Xiao, C. Wang, J. Zeng, Preparation and anti-icing of superhydrophobic PVDF coating on a wind turbine blade, Appl. Surf. Sci. 259 (2012) 764–768. https://doi.org/10.1016/j.apsusc.2012.07.118.

[56] S. Pauliuk, T. Wang, D.B. Müller, Moving toward the circular economy: The role of stocks in the Chinese steel cycle, Environ. Sci. Technol. 46 (2012) 148–154. https://doi.org/10.1021/es201904c.

[57] R. Turconi, A. Boldrin, T. Astrup, Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations, Renew. Sustain. Energy Rev. 28 (2013) 555–565. https://doi.org/10.1016/j.rser.2013.08.013.

[58] E.G. Hertwich, T. Gibon, E.A. Bouman, A. Arvesen, S. Suh, G.A. Heath, J.D. Bergesen, A. Ramirez, M.I. Vega, L. Shi, Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies, Proc. Natl. Acad. Sci. U. S. A. 112 (2015) 6277–6282. https://doi.org/10.1073/pnas.1312753111.

[59] Y. Le Guevel, B. Grégoire, B. Bouchaud, P. Bilhé, A. Pasquet, M. Thiercelin, F. Pedraza, Influence of the oxide scale features on the electrochemical descaling and stripping of aluminide coatings, Surf. Coatings Technol. 292 (2016) 1–10. https://doi.org/10.1016/j.surfcoat.2016.03.019.

[60] GWEC, Global Wind Report 2019, 2020.

[61] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, The ecoinvent database version 3 (part I): overview and methodology, Int. J. Life Cycle Assess. 21 (2016) 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

[62] C. Bulle, M. Margni, L. Patouillard, A.M. Boulay, G. Bourgault, V. De Bruille, V. Cao, M. Hauschild, A. Henderson, S. Humbert, S. Kashef-Haghighi, A. Kounina, A. Laurent, A. Levasseur, G. Liard, R.K. Rosenbaum, P.O. Roy, S. Shaked, P. Fantke, O. Jolliet, IMPACT World+: a globally regionalized life cycle impact assessment method, Int. J. Life Cycle Assess. 24 (2019) 1653–1674. https://doi.org/10.1007/s11367-019-01583-0.