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Towards emissions certification systems for international trade in hydrogen: The policy challenge of defining boundaries for emissions accounting

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ABSTRACT

Hydrogen as a fuel is clean burning, but production can cause substantial greenhouse emissions. Some buyers will prefer to pay a higher price to ensure purchase of low-embedded emissions hydrogen, but it is impossible to determine embedded emissions by examining the end product. Certification of embedded emissions will thus play a key role in the future of hydrogen as a low-emission energy carrier. The boundaries of the supply-chain elements covered in the emissions accounting of certification schemes will have substantial implications for emission-reduction incentives and international tradability. We review the boundary definitions of existing and emerging hydrogen certification schemes. Further, we provide an evidence-based assessment of the magnitude of emissions likely to occur within each boundary of the supply chain. We find varying approaches to boundary definitions in the surveyed schemes. The exclusion of feedstock or transport elements risks ignoring major fractions of supply-chain emissions. In order to balance tradability and emissions-reduction incentives, we recommend that hydrogen certification schemes be designed to follow a modular approach. This type of modular approach would place those with decision-making power over the relevant piece of the supply chain in the position of certifying the emissions within that supply-chain boundary.

1. Introduction

Hydrogen (H_2) is a unique fuel in that associated greenhouse gas (GHG) emissions do not occur at the point of use (as with fossil fuels), but instead occur earlier in the supply chain [1]. Additionally, the quantity of the GHG emissions can vary widely depending on the specifics of the supply chain processes [1]. Low-embedded emissions hydrogen is becoming a premium product, and some buyers will prefer to pay a higher price to ensure that their supply of hydrogen minimizes negative environmental externalities. As an option for power-to-gas value chains increasing exportability of energy, hydrogen is expected to play a large part in energy sector transformation [2,3]. In power-to-gas systems, the source of electricity is key in determining embedded emissions [1,4,5].

However, it is impossible to verify the embedded GHG emissions in hydrogen gas by analysing the final product. The resulting asymmetry of information between buyers and sellers is a market failure, which reduces efficiency and limits the ability of producers of cleaner hydrogen to obtain corresponding price premiums. This will hamper both domestic and international trade, and will hinder jurisdictions wishing to constrain the importation of high-embedded emissions products.

To correct this information asymmetry, there needs to be a reliable, internationally recognized accounting of the carbon emissions associated with marketed hydrogen. This could take the form of a low-embedded emissions certification scheme for hydrogen. By providing a mechanism to place a higher value on

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low-embedded emissions hydrogen, certification may also speed investment in associated renewable capacity. Without this additional valuation, power-to-gas systems face a set of investment incentives that are not closely tied to decarbonisation, and use of renewable energy may add expense to hydrogen production [3,5,6].

Countries have disparate levels of commitment to reducing GHG emissions, and face incentives to use standard setting to maintain the competitive advantage of their own industries. These incentives will shape which parts of the hydrogen supply chain each country prefers to include in the emissions accounting process. For example, setting the boundaries of a hydrogen certification scheme to include only the emissions created during production would preclude emissions from transport, and would likely be preferred by producers that are remote from their customers.

It is highly unlikely that international agreement on the scope of hydrogen certification schemes (including agreement on the boundaries) will emerge in a timely fashion able to support a single, "harmonized" international scheme [7]. In a similar case, as biofuels emerged their trade was initially hampered by fragmented quality standardizations between EU jurisdictions, prior to the creation of a comprehensive standard in 2017 as a first step towards a unified trading system [8]. Fragmented certification schemes for "green" and "low-carbon" hydrogen are also beginning to emerge, and this lends credence to the concern that regionally developed hydrogen certification schemes will similarly lack comparability across borders and that this mismatch could hamper trade [9].

Emergent schemes have discrepancies in both how "green" is defined and where the boundaries are drawn within the supply chain for emissions accounting purposes [9]. If these discrepancies lead to certification schemes not being recognized between exporting and importing jurisdictions, certification will not fill its role of correcting information asymmetries, and trade of low-embedded emissions hydrogen will be hampered. There is therefore a strong case for hydrogen certification boundary design principles that allow interoperability of different schemes.

The IEA considers reaching comparability of standards to be key to scaling up hydrogen markets [10]. We propose that hydrogen certification should follow an "equivalence" principle that facilitates acceptance of differing boundary definitions by various jurisdictions [7,11], while still following common emissions-reduction objectives. As biofuels certification emerged, trade with the EU was limited because the EU only recognizes third country sustainability standards as meeting the EU's sustainability criteria if the third country standard satisfies EU requirements for reliability, transparency, and independent auditing [12]. For hydrogen certifications to broadly support equivalency, it will be important for certification systems to provide the requisite information to demonstrate that hydrogen complies with importer sustainability criteria, and for data to be recognized as accurate [12].

We also note the differing perspectives on what (if any) additional externalities a hydrogen certification scheme should encompass, such as whether it should include environmental impacts of water use, or issues of social justice. Historically, energy exporting nations (including, for example, Australia and Canada) have not always performed well on social justice aspects, particularly in relation to Indigenous landholders, upon whose lands energy extraction often takes place [13–15], but who nevertheless continue to experience "poverty in the midst of plenty" [16,17].

Prior studies have recommended against including these broader issues in hydrogen certification when competing fuel sources such as bio-methane are not required to account for the same externalities [9]. In addition to providing a level-playing field with competing products, a more multi-dimensional scheme would increase negotiation complexity and delay cross-national compliance, as well as negatively impacting small-scale producers by increasing the cost of compliance. Wider externalities may be better addressed by regulation outside the certification framework, or by additional voluntary certification schemes. In this paper, we focus solely on issues associated with GHG emissions (CO_2-e) throughout the hydrogen supply chain, and the ability of governments to create certification systems for these.[1] Our discussion here focuses on hydrogen as an end product, but much of the discussion in this paper is also relevant to other fuels derived from hydrogen, such as ammonia.

1.1. Why boundary definitions matter

Clear determination of the boundaries of certification will be especially important in determining the interoperability of hydrogen certification schemes.

For hydrogen to be traded internationally it must be produced, then converted into a suitable form for long distance transport, and finally shipped or otherwise transported to its destination. Additional steps in the supply chain could also include the supply and purification of water for hydrogen production, local transport, and storage for extended periods. These transportation and storage steps can be associated with high emissions [1]. Prior work has also reported the significant contribution of transportation to overall supply chain emissions, challenging generally believed carbon-neutrality of corn ethanol [18].

Significant emissions can result at each point of the hydrogen supply chain and can vary widely depending on which technologies are used for conversion and transport, as well as whether the hydrogen is produced from the reforming of fossil fuel feedstocks or from electrolysis powered by renewable electricity [1]. In this study, process-based accounting was utilized, mainly because it is predominantly held as a better approach than input-output analysis for tracking processes and their associated material and energy flows related to the production, delivery chain, use, and end-of-life of products [19,20]. However, process-based accounting can only trace the inputs to a certain level, which can result in under-counting the emissions [21]. Although not utilized for our illustrative quantifications here, future research seeking to more precisely quantify hydrogen supply chain emissions within each boundary can build a more complete emissions picture by considering tiered hybrid estimation methods that combine process analysis and input-output analysis to avoid these truncation errors [21–23].

Fig. 1 summarizes the specific emission intensities for some of the different steps in the hydrogen supply chain. We focus on steam methane reforming (SMR) as the dominant hydrogen production method, which produces roughly 10 $kgCO_2$-e/kgH_2. The emissions intensity of SMR can be reduced by up to 90% (best case) if coupled with carbon capture and storage (CCS). Significant emissions are also associated with the production of the feedstock used in fossil-fuel based hydrogen production, corresponding to roughly 25% of the production emissions from SMR. In contrast to SMR, no feedstock or production emissions are incurred for electrolysis of hydrogen powered by renewable electricity.

After production, hydrogen gas is usually compressed to improve its energy density for storage and local transport, by pipeline or by road, to or from ports. For long-distance transport not supported by pipelines, hydrogen must first be converted to a much denser form, either by liquefaction or by embedding in a

[1] Some emerging certification schemes are put forth by private actors, who have different incentive structures than those faced by governments. We focus on government certification due to government ability to shape energy strategies and export markets, both of which are critical for overall energy transitions.

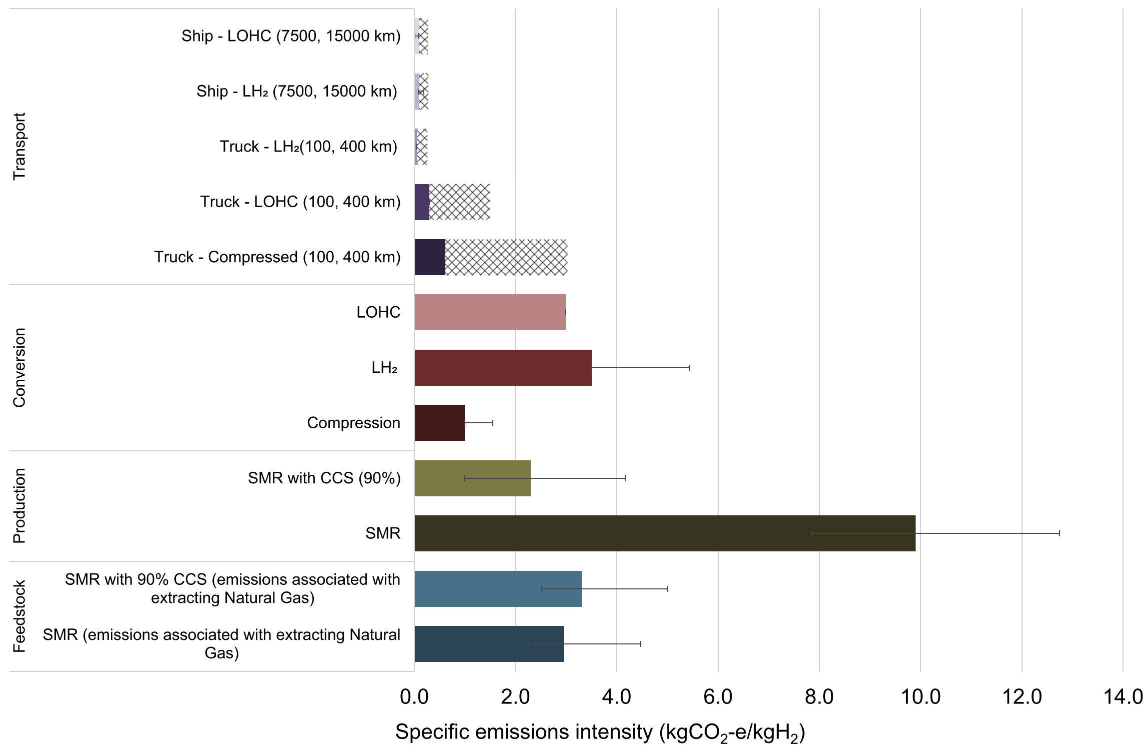

Fig. 1. Specific emission intensities for several boundaries in the hydrogen supply chain, measured in unit mass of carbon dioxide equivalent per unit mass of hydrogen ($kgCO_2$-e/kgH_2). Note that production via electrolysis is projected to run on renewable electricity hence emissions from electrolysis will be zero in the production stage, so electrolysis is not shown as a bar. Error bars represent the range of emissions intensities identified in prior literature for each process. See Notes for process-specific details of intensity definitions and literature sources. In road transport emissions, the solid bars capture the transport related emissions for road trips of 100 km, while the cross-hatched bars represent additional emissions for a 400 km road trip. Similarly, in ocean transport emissions the solid bars represent emissions from voyages of 7500 km (from the Port of Gladstone in Australia to Port of Tokyo in Japan), while the cross-hatched cross-h bars show the additional emissions for a 15,000 km voyage (from Doha Port in Qatar, to Port of Tokyo, in Japan).

Liquid Organic Hydrogen Carrier (LOHC), and then recovered at the destination [10,24,25]. All of these processes require energy, which is often provided by fossil fuel-based energy sources.

Following conversion, the hydrogen must be transported to its final destination, generating more emissions which may be large depending on the distance travelled, and the transport's fuel source. Traditional fuel oil used for shipping is one of the most polluting forms of fossil fuels, and emissions from the maritime sector are not currently included in GHG reporting by governments. However, new international regulations on maritime pollution are emerging and there is a growing movement to decarbonise the industry by switching to clean fuel, including hydrogen and its derivatives like ammonia [26].

Fig. 1 illustrates that a large amount of the GHG emissions embedded in the final, delivered hydrogen product is accrued after production. Even hydrogen generated by electrolysis powered with renewable energy could still have significant embedded GHG emissions by the time that it reaches its destination. For example, emissions due to liquefaction using fossil-fuel based electricity correspond to roughly 30% of the production emissions from SMR. The electricity for any of the conversion processes could be supplied by renewables instead, but if the conversion phase is neglected in the boundary definition of the certification scheme, as it is in many existing schemes, there is no incentive for suppliers to bear the cost of doing so.

Additional complexities in certification emerge if hydrogen is converted into ammonia, which could be reconverted to hydrogen, used as its own end product, or used as fuel, e.g., co-fired in a coal power plant [27]. Conversion of certified low emissions hydrogen into ammonia would not necessarily result in low-emissions ammonia, as it depends on the process used, and whether energy intensive reconversion is required. As such, ammonia could require a separate certification scheme. Though ammonia may be a key emerging energy carrier, low-embedded emissions certification schemes for ammonia and other hydrogen derived fuels are developing more slowly than emerging certification systems for low-embedded emissions hydrogen.

All current or proposed certification schemes include the feedstock and production processes within the boundary, but inclusion of other processes is less consistent (Table 1). Questions remain about whether emissions during construction of production capital should be included, and whether 'scope 3' emissions which occur during the hydrogen use phase (e.g. in the conversion to other products) should also be considered. While no current active or proposed hydrogen certification scheme considers embodied emissions in production capital [9], the California Low Carbon Fuel Standard (LCFS) does consider the use phase [28].

1.2. Current global certification landscape

The (relatively few) hydrogen certification schemes currently active or proposed are outlined in Table 1. A current widely-discussed scheme is the pilot CertifHy scheme in Europe [10,24,29,30]. The CertifHy scheme is a "Guarantee of Origin" (GO) scheme: that is, it considers only emissions associated with feedstocks and production [9]. CertifHy appears to be emerging as a centralizing force in the EU, with The Netherlands expressing intent to follow the CertifHy standard rather than developing their own, the emergent French system under AFHYPAC now being coordinated with CertifHy, and the UK Department for Energy and

Table 1
Supply chain boundaries included in existing or proposed low-carbon hydrogen certification schemes [9,36–39].

	Emissions embodied in capital	Feedstock	Production	Conversion and Reconversion	Transport	Use
AFHYPAC (proposed GO)	No	Yes	Yes	No	No	No
BEIS (consultation process only)	No[a]	Yes	Yes	No[a]	Yes[b]	Yes[b]
California LCFS (active LCA for transport)	No	Yes	Yes	Yes[c]	Yes	Yes
CERTIFHY (pilot GO)	No	Yes	Yes	No	No	No
TÜV SÜD (active certification)	No	Yes	Yes	Yes[d]	Yes	No

[a] Not mentioned.
[b] Recommended as desirable.
[c] Conversion via liquefaction only, reconversion not applicable but implied that reconversion would be included if it was.
[d] Implied but not explicitly mentioned.

Climate Change noting CertifHy as a potential approach for a future system [31]. However, as indicated by the 2018 review by the HyLaw project covering 23 countries within the EU, legislative instruments surrounding GO of hydrogen remain disconnected across the EU, with such fragmentation considered to pose medium to severe barriers to hydrogen trade in most EU countries [31].

Within the Asia-Pacific, key players in hydrogen markets are expected to be Japan, Korea, China, Australia, and New Zealand, as reflected in Roadmap plans extending to 2030 [10]. Shipping will be key to moving hydrogen between these countries. Japan's roadmap documents largely focus on following the European strategy to support trade, with particular attention to CertifHy [30]. The Korean roadmap [32] focuses primarily on transport. New Zealand and Australia both note the importance of green hydrogen certification to building future export markets, with a focus on guarantees of origin [24,33]. Australia additionally notes a tension between the speed of certification development, and lengthy coordination with international partners to create a harmonized standard [34].

Despite the attention currently given to GO certification methods such as CertifHy, some existing certification schemes and national energy plans also consider emissions on the basis of more extended life cycle analysis (LCA). For example, the California Low Carbon Fuel Standard (LCFS) covers emissions at almost all stages including conversion and transport, with the exception of embedded emissions in generating plant [28]. The hydrogen-relevant European Fuel Quality Directive requires emission reductions over time for transport fuels accounting for the full life cycle of emissions [35]. Consultation in the UK highlighted the trade-off between GO schemes being simpler, contrasted with schemes with broader boundaries that extend from transport to the point of use which have the ability to capture additional emissions associated with hydrogen delivery [36].

1.3. There is a pressing need for policy solutions in this area

Certification systems will be crucial for the effective operation of low-emissions hydrogen markets. Certification can facilitate efficient international trade, support global emissions reduction via increased transparency of environmental externalities, and support competitiveness of markets. However, incompatible certification systems between exporting and importing countries could create technical barriers to trade, reducing the efficiency and interoperability of global markets.

Many low-emissions hydrogen certification systems are already emerging, and it is not clear yet which one will become dominant. What does emerge is that emissions from the provision of hydrogen do not just occur within the production stage boundary, but that the emissions occurring within other boundaries can be significant (Fig. 1). There are trade-offs between the environmental desirability of including all GHG emissions across the whole supply chain, and the apparent ease of tradability which drives certification to boundaries covering only part of the supply chain. As a result, emerging hydrogen certification schemes have several different approaches to boundary setting, depending on the interests of the players involved in their development. Certification schemes which capture the entire supply chain will provide a substantial advantage to producers located in the same jurisdiction as their end consumers, suggesting that limiting certifications to life cycle analysis designs could limit tradability for some exporters in international markets.

Efforts to develop hydrogen emissions certification should focus on creating transparent systems that can be easily assessed between importing and exporting countries to identify fulfilment of common objectives, or "equivalency". We propose a modular approach to boundaries that could resolve the conflict between trade and environmental imperatives, and help support the comparability and interoperability identified as key by the IEA.

In such an approach, emissions at each boundary along the supply chain would be certified. An additional advantage of this approach is that the party (or parties) responsible for obtaining the certification would be the one(s) with decision-making power about that part of the chain. For example, a producer of renewable hydrogen might certify production and conversion modules. A producer of SMR hydrogen would certify feedstock and production modules. Producers may then sell the hydrogen (with its certificates) to an exporter who would additionally be responsible for certification of the transport stage. This modular approach of calculating and labelling emissions within each boundary would support trade with jurisdictions taking a variety of boundary approaches, and would lend itself to establishment of equivalency between jurisdictions. For example, if a jurisdiction only required production module certification, this certificate would be visible separate from the transportation module; likewise, if a jurisdiction required all modules from feedstocks through to transport, the modules could be combined to provide this figure. A modular approach would also limit administrative burden on producers to trace only production emissions for the relevant module of certification, likewise at other boundaries. Any number of voluntary or mandatory, private or public "green" certification and labelling schemes may then evolve around the world, in accordance with the tastes of the markets being served. Regardless of which parts of the supply chain are covered by such schemes, participation should be fairly straight-forward to producers and suppliers from anywhere, provided they have certified their emissions at each stage requisite to reliability, transparency, and independent auditing requirements of importing jurisdictions.

2. Notes

Feedstock emissions refer to GHG emissions associated with the natural gas processing, including fugitive emissions and additional energy usage [40]. Feedstock error bars reflect uncertainty as reported by Parkinson et al. [40]. SMR with CCS requires a greater input of natural gas, thus feedstock emissions are higher.

Production emissions include direct GHG emissions from hydrogen production using SMR, with and without CCS at 90% capture rate [40]. Error bars show the uncertainty associated with production emissions as reported by Parkinson et al. [40], considering supply chain contributions of 0.6–1.4% (central 0.9%) fugitive methane emissions and 8.2–14.8 gCO_2/MJ HHV (central 10 gCO_2/MJ/ HHV) to the full emissions range presented in the literature [40].

The conversion technologies considered are: 1) compression of the hydrogen gas to 200–500 bar, assuming an electricity requirement of 2.1–3.3 kWh/kgH_2 [41,42]; 2) liquefaction and subsequent evaporation at destination (LH_2), assuming an electricity requirement of 6.67–10.863 kWh/kgH_2 [41,43] for liquefaction and 0.6 kWh/kgH_2 for evaporation [44]; 3) use of liquid organic hydrogen carriers (LOHC), specifically Dibenzyltoluene (DBT) [45], with estimated emissions of both the hydrogenation and dehydrogenation processes taken from Refs. [42,46]. The embodied emissions in the production of Dibenzyltoluene (DBT) are not included. Conversion error bars illustrate the range of uncertainty in terms of differences in conversion phase emissions intensity estimated in source papers, with these differences stemming from variations in energy intensity values used by prior literature. In all cases the global average emissions intensity associated with electricity production was taken to be 0.475 $kgCO_2$-e/kWh [10]. This non-country-specific average was used to support figure visualization of emission intensities expected to be associated with differences in conversion process as opposed to the separate issue of differences in electricity emissions intensity.

The specific emission intensities for road transport of hydrogen by truck given for compressed hydrogen and LOHC are obtained from Wulf et al. [42], while the information for LH_2 transport with truck is obtained from Reuß et al. [47]. Evaporation rates for the road transportation of GH_2 and LH_2 are taken from Ren et al. [1]. Since, LH_2 and LOHC ocean carriers are still being developed, exact data were not available. Thus, shipping emissions were estimated using data for oil and LNG tankers [45,48]. The average boil-off rate of LH_2 during the ocean transportation was considered to be 0.3%/day [41]. The figure is intended to visualize emissions intensity differences associated with the transport decisions, with the largest factor being mode and distance, hence for brevity omits displaying uncertainty associated with differencing vehicle efficiencies.

CRediT

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Ren L, Zhou S, Ou X. Life-cycle energy consumption and greenhouse-gas emissions of hydrogen supply chains for fuel-cell vehicles in China. Energy 2020;209:118482. https://doi.org/10.1016/j.energy.2020.118482.
[2] Colbertaldo P, Guandalini G, Campanari S. Modelling the integrated power and transport energy system: the role of power-to-gas and hydrogen in long-term scenarios for Italy. Energy 2018;154:592–601. https://doi.org/10.1016/j.energy.2018.04.089.
[3] Mukherjee U, Walker S, Maroufmashat A, Fowler M, Elkamel A. Development of a pricing mechanism for valuing ancillary, transportation and environmental services offered by a power to gas energy system. Energy 2017;128:447–62. https://doi.org/10.1016/j.energy.2017.04.042.
[4] Tschiggerl K, Sledz C, Topic M. Considering environmental impacts of energy storage technologies: a life cycle assessment of power-to-gas business models. Energy 2018;160:1091–100. https://doi.org/10.1016/j.energy.2018.07.105.
[5] Sadeghi S, Ghandehariun S, Rosen MA. Comparative economic and life cycle assessment of solar-based hydrogen production for oil and gas industries. Energy 2020;208:118347. https://doi.org/10.1016/j.energy.2020.118347.
[6] Lynch M, Devine MT, Bertsch V. The role of power-to-gas in the future energy system: market and portfolio effects. Energy 2019;185:1197–209. https://doi.org/10.1016/j.energy.2019.07.089.
[7] Pekdemir C. On the regulatory potential of regional organic standards: towards harmonization, equivalence, and trade? Global Environ Change 2018;50:289–302. https://doi.org/10.1016/j.gloenvcha.2018.04.010.
[8] Horschig T, Billig E, Majer S, Thrän D. Biomethane: local energy carrier or european commodity? Eur Dimens Ger Energy Transit Oppor Conflicts 2019:543–57. https://doi.org/10.1007/978-3-030-03374-3_31.
[9] Abad AV, Dodds PE. Green hydrogen characterisation initiatives: definitions, standards, guarantees of origin, and challenges. Energy Policy 2020;138:111300. https://doi.org/10.1016/j.enpol.2020.111300.
[10] IEA. The future of hydrogen. IEA; 2019.
[11] Bowen D, Hoffmann U. Review of Key Systemic Issues and Findings Resulting from Activities of the International Task Force on Harmonization and Equivalence in Organic Agriculture (ITF) and the Global Organic Market Access (GOMA) Project. 2013. p. 89.
[12] Glinski C. Certification of the sustainability of biofuels in global supply chains. Cham: Springer; 2019. p. 163–85. https://doi.org/10.1007/978-3-030-02499-4_8.
[13] O'Faircheallaigh C. Negotiations in the indigenous world: aboriginal peoples and the extractive industry in Australia and Canada. London: Routledge; 2015.
[14] O'Neill L. A tale of two agreements: negotiating aboriginal land access agreements in Australia's liquefied natural gas industry. University of Melbourne; 2016.
[15] Minerals Council of Australia. Minerals industry: indigenous economic development strategy. 2011.
[16] Langton M, Mazel O. Poverty in the midst of plenty: aboriginal people, the 'resource curse' and Australia's mining boom. J Energy Nat Resour Law 2008;26:31–65. https://doi.org/10.1080/02646811.2008.11435177.
[17] Taylor JT. Change in wellbeing indicators of pilbara aboriginal people: 2001 – 2016 A report to the regional implementation committee. 2018.
[18] Yang Q, Chen GQ. Greenhouse gas emissions of corn-ethanol production in China. Ecol Model 2013;252:176–84. https://doi.org/10.1016/j.ecolmodel.2012.07.011.
[19] Emami N, Heinonen J, Marteinsson B, Säynäjoki A, Junnonen J-M, Laine J, et al. A life cycle assessment of two residential buildings using two different LCA database-software combinations: recognizing uniformities and inconsistencies. Buildings 2019;9:20. https://doi.org/10.3390/buildings9010020.
[20] Säynäjoki A, Heinonen J, Junnila S, Horvath A. Can life-cycle assessment produce reliable policy guidelines in the building sector? Environ Res Lett 2017;12:013001. https://doi.org/10.1088/1748-9326/aa54ee.
[21] Bullard CW, Penner PS, Pilati DA. Net energy analysis. Handbook for combining process and input-output analysis. Resour Energy 1978;1:267–313. https://doi.org/10.1016/0165-0572(78)90008-7.
[22] Chen GQ, Yang Q, Zhao YH, Wang ZF. Nonrenewable energy cost and greenhouse gas emissions of a 1.5 MW solar power tower plant in China. Renew Sustain Energy Rev 2011;15:1961–7. https://doi.org/10.1016/j.rser.2010.12.014.
[23] Wu XD, Guo JL, Chen GQ. The striking amount of carbon emissions by the construction stage of coal-fired power generation system in China. Energy Policy 2018;117:358–69. https://doi.org/10.1016/j.enpol.2018.02.043.
[24] Bruce S, Temminghoff M, Schmidt E, Munnings C, Palfreyman D, Hartley P. National Hydrogen Roadmap - pathways to an economically sustainable

hydrogen industry in Australia. CSIRO; 2018.
[25] Mazloomi K, Gomes C. Hydrogen as an energy carrier: prospects and challenges. Renew Sustain Energy Rev 2012;16:3024–33. https://doi.org/10.1016/j.rser.2012.02.028.
[26] DNV GL. Energy transition outlook 2018 - maritime forecast to 2050. 2018. p. 148.
[27] Stephen H. Crolius. IHI first to reach 20% ammonia-coal Co-firing milestone. Ammon Energy Assoc; 2018.
[28] California Air Resources Board. Low carbon fuel standard. 2020 (accessed June 1, 2020), https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard.
[29] IRENA. Hydrogen from renewable power: technology outlook for the energy transition. 2018.
[30] Ministry of Economy Trade and Industry. The strategic road map for hydrogen and fuel cells. 2019.
[31] Hydrogen Europe. HyLaw online database. 2020 (accessed June 1, 2020), https://www.hylaw.eu/database.
[32] Ministry of Trade Industry and Energy. Hydrogen economy roadmap of Korea. 2019.
[33] Ministry of Business Innovation and Employment. A vision for hydrogen in New Zealand. 2019.
[34] COAG Energy Council. Australian's national hydrogen strategy. 2019.
[35] European Commission. Fuel quality. https://ec.europa.eu/clima/policies/transport/fuel_en. [Accessed 1 June 2020].
[36] Department of Energy and Climate Change. Green hydrogen standard. 2015.
[37] California Air Resources Board. Detailed California modified GREET pathway for compressed gaseous hydrogen from north American natural gas. 2009.
[38] TÜV SÜD. TÜV SÜD standard CMS 70: erzeugung von Grünem Wasserstoff (GreenHydrogen). 2020.
[39] CertifHy. CertifHy. https://www.certifhy.eu/. [Accessed 8 January 2020].
[40] Parkinson B, Balcombe P, Speirs JF, Hawkes AD, Hellgardt K. Levelized cost of CO 2 mitigation from hydrogen production routes. Energy Environ Sci 2019;12:19–40. https://doi.org/10.1039/c8ee02079e.
[41] Ozawa A, Inoue M, Kitagawa N, Muramatsu R, Anzai Y, Genchi Y, et al. Assessing uncertainties of well-to-tank greenhouse gas emissions from hydrogen supply chains. Sustainability 2017;9:1101. https://doi.org/10.3390/su9071101.
[42] Wulf C, Reuß M, Grube T, Zapp P, Robinius M, Hake JF, et al. Life Cycle Assessment of hydrogen transport and distribution options. J Clean Prod 2018;199:431–43. https://doi.org/10.1016/j.jclepro.2018.07.180.
[43] Stolzenburg K, Mubbala R. Integrated design for demonstration of efficient liquefaction of hydrogen. IDEALHY; 2013.
[44] Nexant H2A. Hydrogen delivery infrastructure analysis models and conventional pathway options analysis results. 2008.
[45] Niermann M, Drünert S, Kaltschmitt M, Bonhoff K. Liquid organic hydrogen carriers (LOHCs)-techno-economic analysis of LOHCs in a defined process chain. Energy Environ Sci 2019;12:290–307. https://doi.org/10.1039/c8ee02700e.
[46] Teichmann D, Arlt W, Wasserscheid P. Liquid Organic Hydrogen Carriers as an efficient vector for the transport and storage of renewable energy. Int J Hydrogen Energy 2012;37:18118–32. https://doi.org/10.1016/j.ijhydene.2012.08.066.
[47] Reuß M, Grube T, Robinius M, Preuster P, Wasserscheid P, Stolten D. Seasonal storage and alternative carriers: a flexible hydrogen supply chain model. Appl Energy 2017;200:290–302. https://doi.org/10.1016/j.apenergy.2017.05.050.
[48] Defra. Greenhouse gas reporting: conversion factors 2020. 2020.