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Technoeconomic characterisation of low-carbon liquid hydrocarbons production

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ABSTRACT

With growing attention on low-carbon fuels and chemicals to meet climate targets, careful cost and performance evaluations become critical. These hydrocarbons can be derived from biomass or hydrogen with captured CO_2 via established pathways such as Fischer-Tropsch and methanol synthesis. Techno-economic studies are influential in identifying the economic viability of promising technologies in the absence of reliable industry data. A considerable number of techno-economic studies that represent same technologies exhibit substantial variability in their estimations, posing challenges in decision-making. This work aims to characterise, based on available data, the investment cost and plant performance for the N^{th} (i.e. mature) low-carbon liquid hydrocarbon plants. The extent of data variabilities across technologies are presented and the factors contributing to differences in data interpretation and normalisation are determined. Through a full assessment of existing values, central tendencies for prospective techno-economic evaluations are identified. Processes utilising biomass have the greatest ranges in the investment cost, with higher costs from studies with the highest level of detail and proximity to real-world plant cost estimations. Energy efficiency variabilities arise when tied to plants with multiple outputs. Demonstration scale hydrogen-to-hydrocarbons in relation to economies of scale should be carefully evaluated.

1. Introduction

Large-scale synthetic hydrocarbons production could be important in mitigation pathways, particularly to supply low-carbon jet fuel for aircrafts and building-block chemicals for the petrochemical industry that underpin the global use of plastics [1]. Through the conversion of low-carbon feedstocks into synthetic gas (CO, H_2 and CO_2) coupled with a mature synthesis technology, such hydrocarbons could be produced at very large-scales in the near term [2]. A number of process schemes exist that are separated by two main synthesis steps: Fischer-Tropsch (FT) and methanol synthesis (MS). Utilisation of biomass would involve gasification in the process sequence to provide syngas for the synthesis step, for the cases biomass gasification-FT (hereafter BtL) and biomass gasification-MS (hereafter BtM). Hydrocarbons from electrolytic H_2 and captured CO_2 would require syngas conditioning possibly using the reverse water-gas-shift reactor before the synthesis step for the cases; power-to-liquid via FT (hereafter PtL) and power-to-methanol via MS (hereafter PtM).

Techno-economic studies are influential in identifying the economic viability of promising technologies in the absence of reliable industry data [3]. As no commercial low-carbon synthetic hydrocarbon plants via FT and MS pathways exist, all studies that report on the cost of BtL/BtM and PtL/PtM should be considered prospective [4]. These technologies are increasingly integrated into long-term energy and decarbonisation pathways [5,6]. Since most energy system and integrated assessment models underpinning such pathways seek least-cost technology mixes and overall mitigation costs, precise techno-economic estimations for low-carbon synthetic hydrocarbons are paramount in determining their role in the wider energy system [7,8]. Thus, it is critical to review a number of studies to understand the degree of variability in the investment cost and the performance for these prospective technologies and delve into the cause of the observed variability. Such works would provide some validation for researchers for further comparison studies and provide more accurately informed risk assessments for investors and policy makers.

Haarlemmer et al. [9] evaluates the production and investment costs of BtL plants from 15 publications, followed by another publication by the same author [10] that delves deeper into the variability of BtL techno-economics reviewing additional 4 publications (i.e. 19 in total).

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Abbreviations

BtL	Biomass-to-liquid
BtM	Biomass-to-methanol
CO	Carbon monoxide
CO_2	Carbon dioxide
FCI	Fixed capital investment
FT	Fischer-Tropsch
H_2	Hydrogen
H_2tL	Hydrogen-to-liquid
H_2tM	Hydrogen-to-methanol
HHV	Higher heating value
ISBL	Inside battery limits
LHV	Lower heating value
MS	Methanol synthesis
OSBL	Outside battery limits
PtL	Power-to-liquid
PtM	Power-to-methanol
TCI	Total capital investment
TEPC	Total equipment purchase cost

Holmgren [11] reviews the investment cost of BtL technologies from 18 publications. The three BtL techno-economics review studies provide detailed comparison of the reported investment costs reported until 2015 publication year. BtM investment costs have not been reviewed in detail, albeit Deka et al. [12] provides some comparison of the production cost from 11 publications that produce methanol from low-carbon feedstocks that includes PtM applications. Brynolf et al. [13] reviews publications that conduct techno-economic analysis for power-to-gas and power-to-liquid applications including methane, methanol, DME, FT liquids and gasoline (methanol-mediated). They review 10 publications in total for methanol and FT liquids that are published up to May 2016. Mbatha et al. [14] review the net investment and production cost of PtM technologies from 14 papers.

The existing literature broadly conclude each techno-economic assessment rationalises and uses a different set of assumptions in their process design and cost analysis which lead to deviations in the results. This could overestimate future costs or even worse provide false confidence in the technology [7]. Yet aside from a single study that review BtL publications in depth that was published in 2013 [10], there is limited understanding in the degree of the discrepancies in the techno-economic data reported in the recent literature for BtL, and no such work is available for BtM, PtL and PtM. In the context of their growing significance in emissions mitigation pathways as mature fuels and chemicals synthesis routes, it is crucial to understand and address these discrepancies and uncertainties to mitigate potential risks where possible. This paper aims to systematically compare and evaluate recent techno-economic data until May 2023 using a coherent methodology to determine sensible ranges. It also seeks to provide guidelines to standardise data comparison for future studies relying on such information for extended assessments which the current literature does not explicitly provide.

2. Methods

2.1. Techno-economic data identification and screening

A comprehensive literature review is conducted to understand the performance and investment cost of synthetic hydrocarbon plants that produce FT fuels or methanol from lignocellulosic biomass, municipal solid waste, or hydrogen with captured CO_2. The publications are separated via synthesis pathways that utilise FT or MS and via feedstocks. A systematic search on the ISI Web of Science database is managed using advanced search terms for each technology category listed in Table 1.

The search yielded 439 results, dating back to the publication year of 2009. The title and the abstract of these studies were screened individually to exclude papers that did not evaluate low-carbon feedstocks or process economics. This identification process retained 134 publications for review to match the purpose of the current study. Then, the pool of remaining papers was screened based on three criteria: (1) the study should provide cost assessment of the entire plant from feedstock to purified or refined product, (2) the study should use conventional and proven technologies, unit operations and feedstocks, and (3) should provide original process designs or techno-economics without relying on the cost evaluation from other studies. The screening step led to 35 peer-reviewed studies for detailed review. The exhaustive list of studies excluded during the screening process, along with the rationale for their exclusion, can be found in the Supplementary material. Following this step, seven influential reports that undertake in-house techno-economic analysis of the relevant technologies were taken into the literature survey. Namely, the International Energy Agency [15,16]; the World Economic Forum [17]; the National Energy Technology Laboratory [18]; the German Energy Agency [19]; the National Renewable Energy Laboratory [20]; the Pacific Northwest National Laboratory [21,22]; and the International Renewable Energy Agency [4]. The detailed review process also uncovered three unidentified publications during the Web of Science search [23–25] that met the criteria for review.

The entire process results in 25 and 20 publications for FT and MS routes, respectively, which lead to 78 individual processes. The investment cost and the energy efficiency of synthetic hydrocarbon technologies are underpinned by those process designs in this section.

2.2. Extraction of techno-economic data

2.2.1. Investment costs

In capital cost estimations, the total capital investment (TCI) is the sum of direct fixed capital investment (FCI) (i.e. cost of designing, constructing and installing a plant), working capital (i.e. cost for running the plant including investment in raw materials, consumables, labour and utilities) and start-up cost (i.e. single investment to prepare a new plant for operation and validation). Generally, the latter two would be estimated as a percentage of the FCI. The FCI is typically calculated as a sum of four categories: inside battery limits (ISBL) investment; outside battery limits (OSBL) investment, engineering and construction cost,

Table 1
Formulas used in the Web of Science advanced search.

Technology	Web of Science search formula	Number of results
BtL (FT)	ALL=((“techno-economic”) AND (“BtL” OR “Biomass-to-liquid” OR “Municipal solid waste” “fuel” OR “Liquid transportation fuels” OR “Jet fuel” “Fischer-Tropsch” OR “Diesel” “Fischer-Tropsch”))	205
PtL (FT)	(ALL=((“techno-economic”) AND (“PtL” OR “E-fuels” OR “synthetic fuels” OR “electrolysis” “Fischer-Tropsch”))) OR (ALL=((“economic assessment”) AND (“CO2” “liquid fuels”)))	113
BtM (MS)	(ALL=((“techno-economic”) AND (“BtM” OR “Biomass-to-methanol” OR “biomass” “methanol synthesis” OR “biomass” “methanol-to-gasoline” OR “biomass” “MTG” OR “Municipal solid waste” “methanol synthesis”))) OR (ALL= ((“technoeconomic”) AND (“Biomass” "methanol-to-gasoline")))	60
PtM (MS)	((ALL=((“techno-economic”) AND (“PtM” OR “Power-to-methanol” OR “CO2” “methanol synthesis” OR “CO2” “green methanol” OR “CO2” “renewable methanol”))) OR (ALL=((“economics”) AND (“power-to-methanol" OR “CO2” “methanol” “hydrogenation”))))	137

and contractor's fee and contingency charges. The total equipment purchase cost (TEPC) of the plant is estimated first which underpins the ISBL investment and the latter three cost categories in the FCI. The TEPC is estimated using equation (4) which accounts for the economies of scale. Full description of the components of the capital investment is extensively reported [3,26–29].

Here, the TCI, energy efficiency, plant lifetime, annual operating hours, plant capacity, reported feedstocks, and process and technology specific characteristics are extracted from the selected studies. The production cost and feedstock prices are excluded from this review due to questions over the sensibility to the business models, and additionally, heavy regional influences, particularly for the electricity prices affecting PtL/PtM technologies.

The costs are updated to the average annual currency of $2022 using the reported data year of the respective studies, and if unreported, the data year is assumed to be two years prior to the publication year which is the most common among reported studies. The capital costs are adjusted to 2022 with the annual UCCI index (formally known as IHS/CERA index), which tracks the timely average equipment and construction costs and allows updating historical equipment costs. This conversion is based on equation (1). One could argue that for a higher accuracy in the equipment cost conversion, monthly CEPCI could be applied [30]. However, such data is not sensibly documented in the selected studies and thus deemed it would present higher margin for error.

$$(Purchase\ price)_x = (Purchase\ price)_{base} \times \frac{(Cost\ index)_x}{(Cost\ index)_{base}} \quad (1)$$

In extracting the techno-economic parameters for PtL/PtM, the costs and the efficiencies of electrolysis and DAC are excluded, if applicable. Thus, examining the techno-economics of these technologies involves considering readily available and pure streams of H_2 and CO_2, or hydrogen-to-hydrocarbons. This decision was made because there are extensive techno-economic studies in the literature that focus on electrolysis and DAC and their expected cost reductions in the future [15, 31], and the impact of variation in the assumed cost of those units could mislead the discrepancies in the investment cost of the remaining steps (i.e. synthesis and refining). When scope of the PtL/PtM span across including electrolysis and DAC plants in the integrated plant, the costs associated with those units from the TCI are excluded via disaggregation and the TCI and the efficiencies from the point of H_2 and CO_2 as starting feedstocks are extracted (hereafter, PtL and PtM are referred to as H2tL and H2tM, respectively). The plant scopes for the four technologies examined in this analysis are illustrated in Fig. 1. With regards to the methanol-route, limited studies include methanol-to-hydrocarbons in their techno-economic analyses, with a vast majority focusing on the production of methanol as the final product. Consequently, this aspect was not included in this work. In practice, the role of methanol as a precursor for longer chain hydrocarbons (e.g. jet fuel; diesel) or high-value chemicals (e.g. ethylene; propylene) is a contentious subject [32].

2.2.2. Energy efficiencies

The efficiency parameters (i.e. the fuel input and output in energy terms) are adjusted to the higher-heating value (HHV) basis. In cases when the feedstock and the product heating values were reported in lower-heating value (LHV), equations (2) and (3) were used in the conversions. The heating values reported for H2tL and H2tM are broadly consistent (i.e. hydrogen, methanol and the resulting paraffinic hydrocarbon fuels) across the studies. On the other hand, the heating values for specific biomass feedstocks vary between 17 and 21 MJ/kg HHV. Each study would report the assumed heating value of biomass feedstocks, typically in LHV, and this posed a challenge in the conversion process as the equivalent HHV for particular feedstocks in specific regions were not easily available. This is relevant for a few studies; however, for the conversion of the entire energy efficiency of a BtL plant that use generic wood pellets, the LHV to HHV conversion factor resulted in the value of 1.003, meaning that the discrepancy factor in the LHV and HHV of biomass and FT kerosene were close to equal. In other words, the disparity in the results due to mismatching heating values, particularly for BtL is expected to be low. In several cases, small amounts of electricity, heat or light gases are considered as secondary products from FT, and the heating content of those outputs are embedded in the normalisation.

$$(Energy\,efficiency)_{HHV} = (Energy\,efficiency)_{LHV} \times \frac{(Feed\,HV)_{LHV}}{(Feed\,HV)_{HHV}} \times \frac{(Product\,HV)_{HHV}}{(Product\,HV)_{LHV}} \quad (2)$$

$$(Cost\,per\,unit\,of\,product)_{HHV} = (Cost\,per\,unit\,of\,product)_{LHV} \times \frac{(Product\,HV)_{LHV}}{(Product\,HV)_{HHV}} \quad (3)$$

2.3. Normalisation to a reference capacity

The TCI and reported plant output capacity have been extracted for analysis. Additionally, a 400 MW (output) reference capacity is assumed to facilitate comparison among numerous results with varying plant capacities. This reference scale is a reasonable balance between (i) recognising the difficulties in sourcing large amounts of low-carbon resource, and (ii) achieving sufficient level of economies of scale. The initial TCI is converted using the classic cost estimation formula shown in equation (4). This equation represents the increase in the equipment

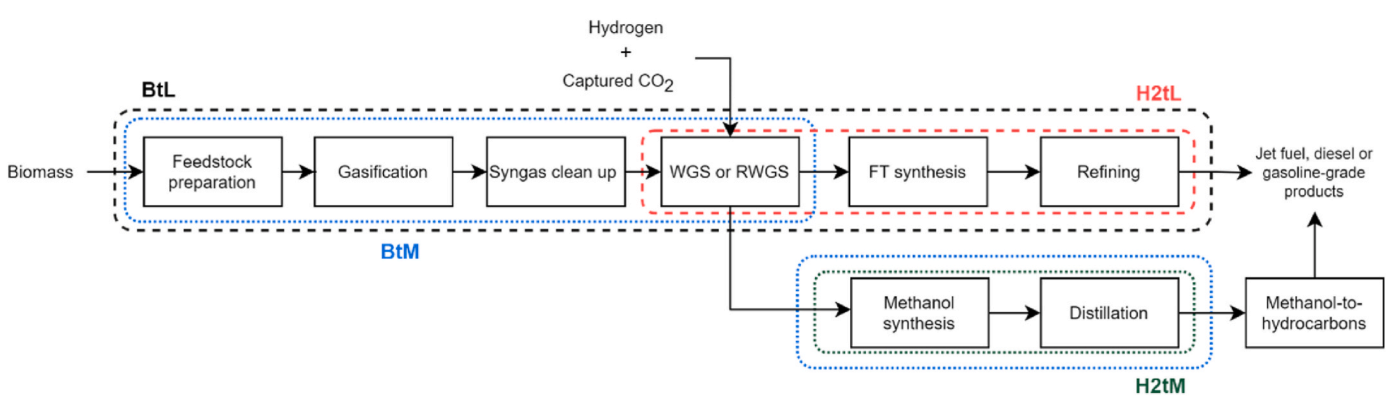

Fig. 1. Simplified technology scope for BtL (black), BtM (blue), H2tL (red) and H2tM (green), examined in this study. FT in dashed and MS in dotted lines. RWGS is reverse-water-gas-shift reaction, that is relevant for direct streams of H_2 and CO_2, and biomass systems would employ water-gas-shift reaction (WGS). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

cost of a unit or in capital cost with increase in capacity at constant technology. A scaling factor (or exponent) smaller than 1 would result in lower investment costs as the capacity increases, indicating the presence of economies of scale. The scaling factor depends on the equipment involved in the plant, and the value of 0.6–0.7 is usually the standard for most equipment in hydrocarbon plants [3,33].

$$(Cost\ of\ equipment)_x = (Cost\ of\ equipment)_{base} \times \left(\frac{Capacity\ x}{Capacity\ base}\right)^{scaling\ factor} \tag{4}$$

The assumed extrapolation exponents are subject to the original authors' rational decisions. The review identified a number of studies for BtL, and to a smaller degree, BtM, that provide detailed documentation of the assumed scale factor for each process equipment [9,20,34–40]. It found that only a single study for each technology opted for a universal value applied to all process equipment (0.65 and 0.67), rather than assigning different factors [41,42]. On the other hand, this approach of exhibiting less detail is prominent across H2tL and H2tM studies. For H2tM, aggregated values of 0.6 [43], 0.65 [24] or 0.67 [44] are used, while a value of 0.7 [45,46] is used for H2tL. This information was inaccessible in several studies [32,47–49] particularly for H2tM. For this analysis, 0.67 is adopted as the default scale factor, which is commonly used and serves as the default value for a majority of units in the technologies examined.

3. Results

Fig. 2 shows the distribution of the publication year of the selected studies.

BtL publication output is consistent throughout the chosen period until 2018. On the other hand, research on BtM was conducted in the early 2010's primarily commissioned by the U.S. Department of Energy for the purposes of producing gasoline for the energy security of their road transport sector. Cost of H2tL is explored consistently, with the first publication in 2012 and the last selected paper in 2020. H2tM papers are less evenly distributed, growing in number across years with 2020 with the greatest number of research output. Given the burgeoning literature that has been reviewed, further studies in the future are unlikely to substantively affect the conclusions of this study. More precise estimations would only be possible after a few commercial scale plants are designed and under construction after passing safety assessments [9].

The comprehensive list of interpreted and normalised values for investment cost and energy efficiency for an Nth plant for BtL, BtM, H2tL and H2tM can be found in the Supplementary material.

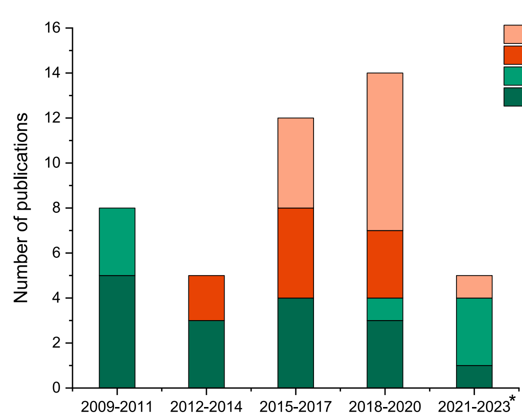

Fig. 2. Number of techno-economic publications assessed per three years. *This sample is underpinned by the Web of Science search as of May 2023 and additional studies that meet the criteria could be published in the remainder of the year.

3.1. Fischer-Tropsch plants

3.1.1. Biomass-to-liquid

Among the technologies, BtL has the most extensive collection of techno-economic data available and covers the widest range of plant capacities, spanning 40–747 MW (FT fuels). The investment cost or the efficiency of the plant show no dependency to the type of gasification technology, FT reactors or the biomass feedstock, aligned with the findings of Haarlemmer et al. [9] and Holmgren et al. [50]. The range of the normalised investment cost is for the reference 400 MW (fuel) plant and the energy efficiency is visibly high for BtL, ranging from 20 to 137 $/GJ and 36–66% HHV, respectively. Disparity in the cost and the efficiency is reasonably comprehensible when delving deeper into the studies which are discussed in detail throughout the latter sections.

3.1.2. Hydrogen-to-liquid

Aside from the PtL electrolysis and DAC technologies from (i.e. H2tL), the remaining processing steps are already relatively mature. The reactor and catalyst for the FT technology have potential for improvement and the reverse-water-gas-shift reactors have not yet been scaled [51].

Without the cost burden associated with gasification (including biomass preparation and syngas clean up), the investment costs of the remaining processing steps for H2tL are generally low (i.e. reverse-water gas shift reaction, FT and refining). Due to the low capacities expected at present, the reported studies are smaller plants compared to BtL, and half the reported studies propose plants that are smaller than 50 MW capacity with the highest reported capacity reaching 323 MW [52]. Nevertheless, concerning global decarbonisation, it is anticipated that H2tL technologies will demonstrate substantial scale up. Albeit Kreutz et al. [53] state that the benefits will dwindle from scales above 700 MW as the refineries would require multiple units in order to produce the desired quantity of fuels, with scale factors for these units approaching 0.9.

3.1.3. Ranges in the investment cost

Fig. 3 shows the distribution of the investment costs per reported plant capacities for FT technologies. The use of the scale factor is evident across studies with economies of scale clearly observed for both BtL and H2tL processes. The floor investment cost is dominated by studies by Baliban et al. [34] and Niziolek et al. [35] for BtL, that are outputs of the same research group in Princeton University. The plant designs from

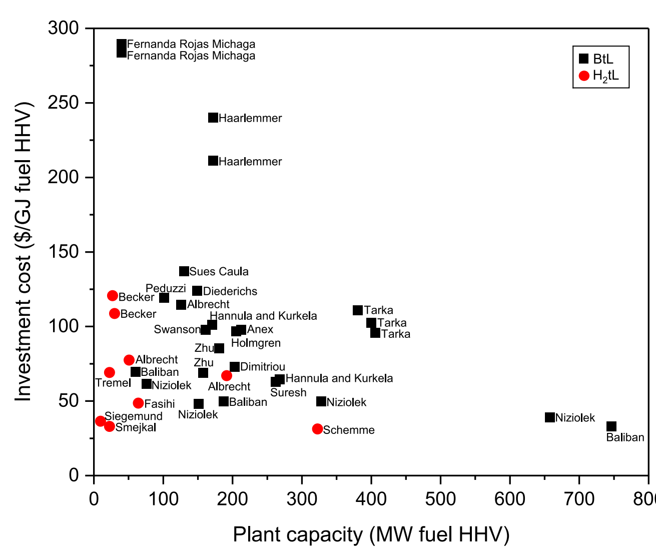

Fig. 3. Investment cost for BtL (black) and H2tL (red) technologies against the reported plant fuel capacity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

both studies demonstrate the highest overall energy efficiencies among their respective BtL facilities, that is illustrated in Section 3.3. This research group also demonstrate processes with optimal carbon capture rates for BtL [54]. It is expected that the TCI of a BtL plant in the real world will not go below the values reported from those studies which explore highly developed BtL superstructures and refinery design. Additionally, sourcing enough biomass to operate such a large plant could be impractical for a single site, in combination with the dwindling effect of cost reduction due to larger scales. This proposition likely applies to the energy efficiencies as these plants are anticipated to exhibit optimal performance concerning the techno-economic characteristics of a BtL facility.

Haarlemmer et al. [9] reported the highest normalised investment cost for the reference 400 MW scale plant. This could be attributed to a number of factors. First, the additional costs estimated on the basis of the ISBL cost in this study is relatively extensive, with 2.2 as the factor between the ISBL and the TCI. Second, this study uses ProSimPlus30 software while the vast majority of the sample select process simulation software from AspenTech (i.e. Aspen Plus or Hysys) potentially causing further variabilities in the insights. Third, the processes modelled in this study include power plants valorising the available tail gas and a sulphur plant in their utilities, thus maximising the utilisation of valuable process streams. One of the processes also include the cost and energy needs for the oxygen production facility to meet the needs of the entrained flow gasifier. This characteristic is shared by Tarka [18], a report commissioned by the U.S. Department of Energy, which similarly includes power generation blocks, extensive tail gas processing and re-reuse and recovery of useful products such as hydrogen and sulphur. Consequently, these two studies exhibit the highest normalised investment cost and relatively low energy efficiencies.

Three plant designs represent the floor cost of small and medium sized H2tL technology. It is worth noting that the investment cost for small plants reported may need to be interpreted with care. For instance, Smejkal et al. [46] does not explicitly specify the products and rather refers to them as liquid fuels. There is significant output of C_2–C_{15} hydrocarbons in this study, suggesting that costs associated with refining may not be considered. Siegemund et al. [45], a report commissioned by the German Energy Agency, conducts estimation in the investment cost of a PtL facility in a disaggregated manner (i.e. listing specific investment costs for electrolysis, hydrogen storage, CO_2 supply and synthesis). However, it is not clear whether the "synthesis" refers to only the FT unit or with the remaining refining steps also embedded in the term. The low investment cost for such a small capacity suggest that it is likely to be the former. For such small plants, costs related to refining of the FT synthetic crude is expected to be disproportionately expensive and it is misleading to sort FT synthetic crude with FT refined product as the same commodity. The investment cost of the medium sized plant presented in Schemme et al. [52] appear reasonable when compared to BtL plants of similar scales, when factoring out the costs associated with the syngas production.

3.1.4. Product distribution

The FT pathway is inherently associated with co-products, regardless of the chosen slate to maximise. It is not possible to focus entirely on a single refined product (e.g. diesel), and the products distribution corresponds to the operating conditions and the type of catalyst employed, following the Anderson–Schulz–Flory (ASF) distribution [55]. The product split is poorly documented for 46% of the studies, with a quarter of the studies employing a generic term such as "liquid fuels" for the output. When reported, diesel is by far the most popular product that is maximised, with a couple of recent publications maximising the jet slate [17,40]. The highest proportions reported for diesel, jet fuel and naphtha (or gasoline) are 76%, 75% and 30% of the total plant output, respectively.

3.2. Methanol synthesis plant data

3.2.1. Biomass-to-methanol

Interestingly, there are less BtM studies as compared to BtL, with half of the sample published in recent years (2018, 2021 and 2023). This suggests the dominant research focus on FT and first-generation bio-fuel routes for the production of low-carbon road transport fuels in the earlier years, and the recent interest in using methanol as a low-carbon platform chemical. Commercially, there are numerous large-scale (reportedly up to 638 MW) bio-methanol plants planned and under engineering in the U.S. and Europe that provides the projected investment cost which reduce the need for techno-economic estimates via software simulations. Company estimates of the investment cost appear to align with the techno-economic studies when accounting for scale.

3.2.2. Hydrogen-to-methanol

Similarly to H2tL, most of the units within the H2tM is already extensively applied in the manufacturing of gas and coal-based methanol that contributes to the 100 Mt of methanol produced annually [4]. In effect, this technology is already very mature, and involve the smallest number of processing equipment among the four technologies, reducing the uncertainties in the cost estimations. This is reflected in our results in Fig. 5.

Whether direct or two-step hydrogenation of CO_2 will be selected for commercial H2tL plants is still contentious, with majority of the techno-economic studies in this analysis interested in the former. Yet the capital cost differences between the two approaches are marginal and does not meaningfully influence the TCI. Kourkoumpas et al. [44] assumes the same reactor from syngas synthesis can be used for the direct CO_2 hydrogenation.

3.2.3. Ranges in the investment cost

Fig. 4 shows the investment cost against its reported capacities for BtM and H2tM technologies. Similarly, to Fig. 3, when compared against each other, the costs from the selected technologies appear reasonable with economies of scale clearly visible. The floor costs for H2tM below 100 MW should be taken with care as Bellotti et al. [24] and Zhang and Desideri [56] are studies that estimate the cost of electrolysis integrated into their cost estimation, and it is possible that the TCI taken into this

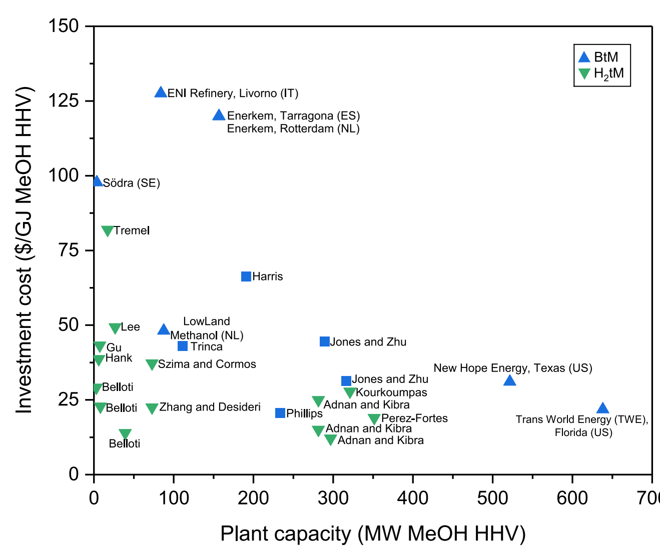

Fig. 4. Investment cost for BtM (blue) and H2tM (green) technologies against the reported plant capacity. For BtM, industry data reported to IRENA and Methanol Institute [4] are represented in triangles, and techno-economic studies are represented in squares. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

analysis could not be reflective of the true sum. As mentioned previously, when implemented at large scale as a mature technology, the floor costs are unlikely to reach below values represented in Adnan and Kibria [49]. It is anticipated that this will also apply to BtM, with Phillips et al. [20] setting the floor costs expected in the future. Equally, it is important to consider the ceiling costs in studies that consider the future value of such technologies as reflected with study by Harris et al. [57] as there are substantial precedent for the overblown cost of hydrocarbon facilities for gas or coal applications.

3.3. *Synthesis of techno-economic characteristics across technologies*

Fig. 5 shows the spread in the normalised investment cost of the reference 400 MW (output) low-carbon hydrocarbon plants, and its relationship with publication year and plant capacity.

BtL, the technology most frequently explored in the techno-economic literature, displays the widest differences in the normalised investment costs, with values ranging from 20 to 137 $/GJ. This is followed by BtM with the second widest range (4–64 $/GJ). There could be two reasons for such outcomes. First, the two technologies display the longest spread in the publication years for the selected studies, as the field of biomass utilisation to produce transport fuels has been explored extensively for decades as illustrated in Fig. 2. The influence of publication year on investment cost, in Fig. 5b–is probably caused by incremental changes to the appraisal methodology [10]. Second, these technologies contain the longest and most complex chemical processes, so authors have greater latitude for subjective decision-making in their design of the process. In contrast, H2tL and H2tM technologies show visibly smaller ranges. Slightly broader ranges are evident for H2tL due to the additional refining steps involved. The intensified research focus on H2tM in recent scientific literature, particularly within the last five years, appears to have fostered mutual influence among authors conducting techno-economic studies.

Interestingly in the case of BtL, while the difference between the maximum and the minimum values are significant, the spread for the studies that fall within the 25–75th percentile is relatively narrow and display a degree of consistency. For H2tL, the 25th percentile range is almost equivalent to the minimum value. This is attributed to a number

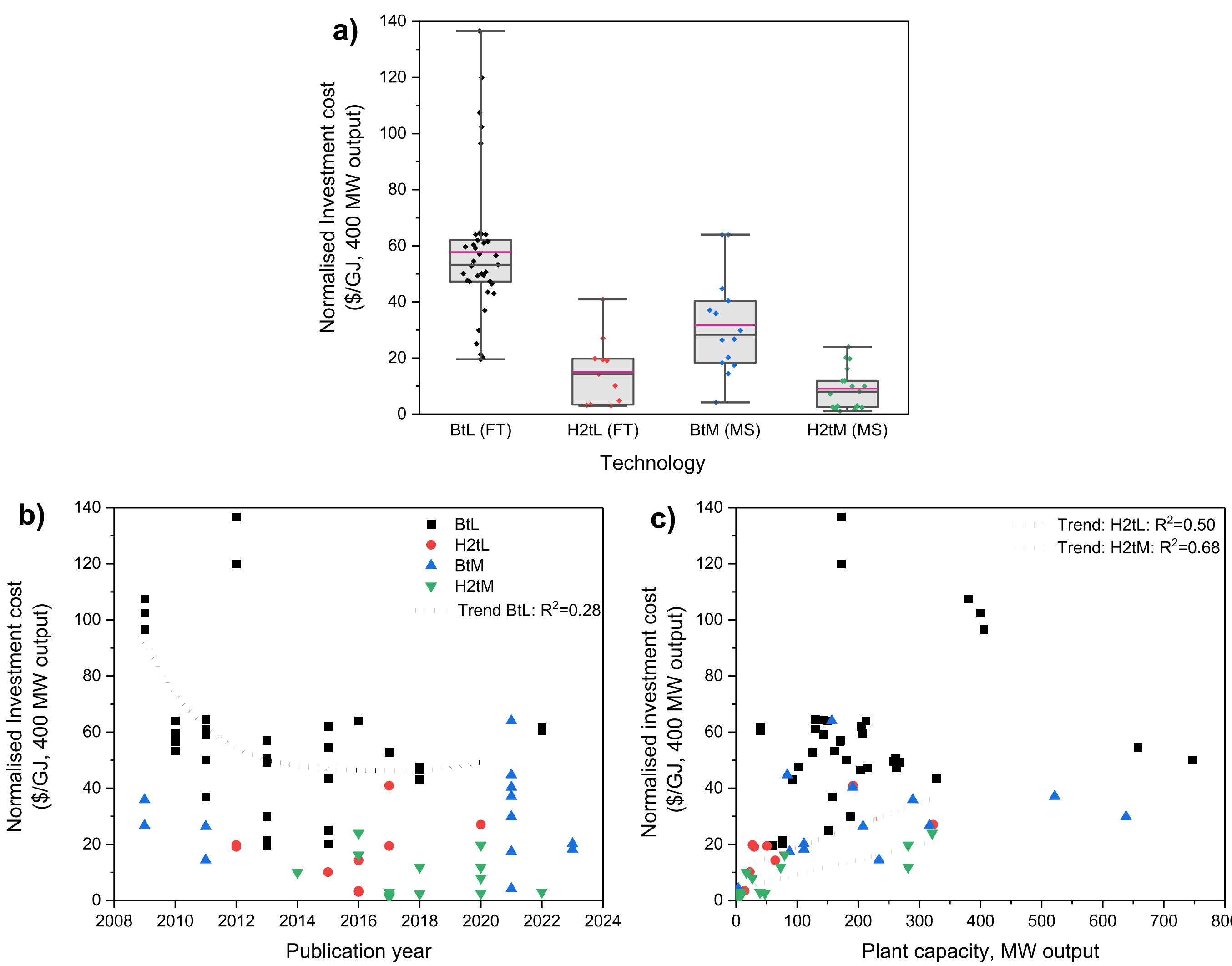

Fig. 5. The normalised investment cost of 400 MW (output) plants for BtL (black), H2tL (red), BtM (blue) and H2tM (green), calculated using eq (4). 5a) boxes and whiskers plot of the normalised investment cost. The mid lines refer to the median (grey) and the mean (pink). Lower and upper quartiles are 25 and 75% of the sample, respectively. Whiskers cover the entire data set from the minimum to the maximum normalised value. 5b) and 5c) shows the normalised investment cost against the publication year and the plant capacity (MW output), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of processes from a selected studies that could be misrepresenting the H2tL technology scope and exclude cost associated with refining, as discussed in Section 3.1.3. H2tM show the most consistency for investment costs that lie between the quartiles, and the minimum and the maximum values are relatively small compared to other three technologies.

A discernible trend is evident in the normalised investment cost relative to the reported capacity for H2tL and H2tM as depicted in Fig. 5c. While most of the examined BtL and BtM processes represent commercial plant scales with capacities above 50 MW, around 56% of the reported H2tL and H2tM processes fall below this scale. Notably, this places a greater level of influence on the assumed scaling exponent when determining the normalised investment cost for the 400 MW reference scale plant. When the scale factor is adjusted (from the base assumption of 0.67) to 0.6, the differences for the normalised investment costs remains below ±20% for commercial scale plants. Such difference increases considerably for plants smaller than 30 MW, resulting in the range of ±20–44%. Moreover, the same adjustment of the scaling exponent for capacities below 10 MW results in the differences of ±30–44%. The differences in normalised investment costs become more pronounced when comparing the outcomes associated with scaling exponents of 0.6 and 0.7. This highlights the excessive leniency of the classic scale-up formula (equation (4)), which accounts for economies of scale, when applied to plants with very small initial scales.

The median capital cost is lower than the mean for all four technologies, as studies in the upper end of the spectrum project substantially higher costs than the rest. Taking the median value to represent the sample would decrease the dependence on those studies. However, upon examining the techno-economic evaluations conducted in those studies, it becomes apparent that they offer the highest level of detail, reliability, and proximity to real-world plant cost estimations [9,18]. Therefore, it could be appropriate to take the average rather than the median when taking from a sample of this nature or alternatively, take a conservative approach and entirely base the costs on a number of studies that lie on the upper end of the sample. This observation also extends to the energy efficiencies, where the most comprehensive studies reveal the highest levels of energy loss, leading to lower overall values, as shown in Fig. 6b.

Fig. 6 shows the variability in the energy efficiencies across the technologies, alongside their relationship with normalised investment cost, publication year and plant capacity. No apparent trends are

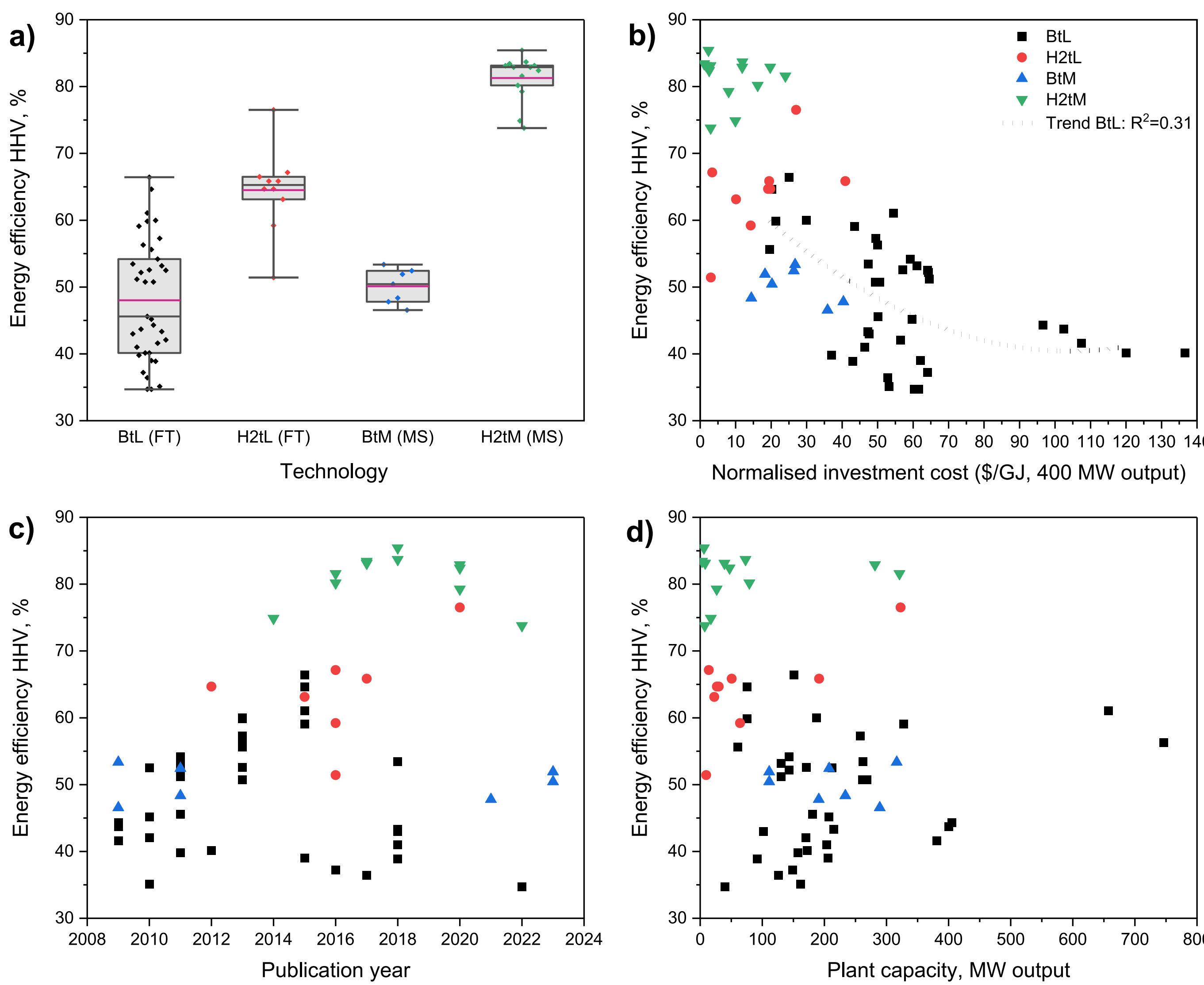

Fig. 6. a) boxes and whiskers plot of the energy efficiencies (HHV). The mid lines refer to the median (grey) and the mean (pink). Lower and upper quartiles are 25 and 75% of the sample, respectively. Whiskers cover the entire data set from the minimum to the maximum normalised value. 6b–d) shows the energy efficiency as a function of the normalised investment cost, publication year, and the plant capacity (MW output), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

observable concerning the energy efficiency in relation to the latter two variables.

BtL showcases a substantial efficiency range, exhibiting a notably more uniform distribution in contrast to the associated plot for the normalised investment costs, as indicated by the quartile ranges. Most plant designs at the higher end of BtL efficiency range (8 out of 9) stem from a single research group [34,35] that explores highly optimal thermo-refinery concepts. The extent of efficiency variance shown for BtL is closely paralleled by the alternative FT technology (H2tL), whereas technologies yielding methanol exhibit relatively uniform values. This observation suggests that the diverse outputs inherent in FT hydrocarbon synthesis could be the primary factor contributing to the data spread.

4. Discussion

Ranking the reliability of techno-economic studies based on process characteristics is challenging as they are largely independent. On a related note, drawing objective trends in the variability in the data stemming from the process variations and equipment data sources is difficult due to the lack of overlap in the data sources and insufficient documentation. This aligns with the conclusions of previous works [10, 50]. Expanding on the works of Haarlemmer et al. [10], this analysis finds author choices in the reactor technologies (i.e. gasifier and FT and methanol synthesis reactors), the process schemes relating to biomass handling (e.g. torrefaction) and the direct CO_2 hydrogenation vs. the syngas pathway for H2tM have negligible impact on the investment cost and the process efficiency.

However, the level of detail in utilising valuable process streams strongly influences the total equipment costs that underpin the ISBL and TCI. For instance, Fernanda Rojas Michaga et al. [40] and Haarlemmer et al. [9] considers full valorisation of by-products such as sulphur and tail gas such that additional units are required. Holmgren et al. [50] also notes the departure of Haarlemmer et al. [9] from the rest of the BtL studies. Most studies would place less emphasis on such detail thus driving down their total equipment cost. In reality, the business cases of such plants are fragile and must be as profitable as possible, so the approach taken from the former could be more sensible.

Detailed reports commissioned by the U.S. Department of Energy [18,20–22] estimate the true cost of building such plants at commercial scale in several regions. They are the closest from the pool of evaluated studies to the Class 3 cost estimates as defined by AACE International [3], while most of the software simulation studies would fall within Class 4 or 5 ("ballpark" estimates without essential design information and only requiring the flowrate) with the accuracy of ±30%. Notably, these studies fall within the centre range of the data set as characterised in Section 3.3 with evidenced ratios between the ISBL and the TCI (~2.5), rendering them well-suited for extended assessments with lower risks.

Comparable studies examining H2tL and H2tM in such detail are unavailable in the existing literature. Studies which cover the two technologies model smaller-scale plants due to the relatively recent interest, challenges in scaling up associated technologies like electrolysis and DAC and expected delays in start years due to high feedstock prices. While the shorter process chain reduces uncertainties in the energy efficiencies, precise estimates of investment cost of an integrated large-scale plant remain uncertain, evidenced by the highly varied ratio between the ISBL and the TCI. For H2tM studies, the Lang factor, representing the ratio of equipment cost to TCI, demonstrated high variability ranging from 2.27 [49] to 5 [58]. These ratios are generally assumed in an aggregated manner for hydrogen-based technologies, for instance, Tremel et al. [43] covers all aspect of OSBL costs with a single assumption. However, a degree of consistency is identified for the cost and performance of H2tM under the same simulation tools for AspenTech [49,56,59] and CHEMCAD [32,48].

4.1. Guidelines to enable intercomparison of techno-economic data

Performing a balanced comparison of techno-economic studies for low-carbon synthetic hydrocarbons plants is a challenging exercise due to variations in both data availability and the transparency of methodological assumptions between studies. Here, practical guidelines are proposed for future studies to enable holistic comparisons and wider use of their data:

- The TCI is highly influenced by the plant scale for industrial chemical and fuel manufacturing plants. Such detail often is missed in studies which examine synthetic hydrocarbons under systems decarbonisation [15], potentially causing further variability in the literature. Thus, it is crucial to select a reference capacity and operate with a scale factor between 0.6 and 0.7 after identifying the most appropriate factor for the relevant plant. It is also important to note the impact of economies of scale will dwindle and have negligible influence for plants larger than 700 MW [53]. Additionally, it could be advisable to avoid using the traditional scale-up formula for small plants below 30 MW, and especially for those originally sized below 10 MW.
- The selection of the reference data year could be influential to the TCI, as it underpins the currency exchange or the UCCI index to reflect the equipment cost of the selected year. As noted by Haarlemmer et al. [9] and Holmgren et al. [50], minor discrepancies arise from short timeframes, but for longer or specific updating periods, variations in TCI could reach up to 30%. Avoiding such specific updating periods (that depend on the specific index), and studies conducted decades prior could reduce these risks.
- It is crucial to use techno-economic data which model the full process chain. These steps are not always taken from the input to the desired hydrocarbon product, particularly for H2tL. For instance, the cost estimation of Siegemund et al. [45] was questioned in Section 3.1.3, that provides the floor cost for H2tL from a very small plant, and a relatively influential report published a year later underpin their analysis referencing those investment cost [60]. Similarly, Smejkal et al. [46] is an influential work for extended assessments that utilise FT in an PtL context. Taking such data for further analysis would not be the best reflection of what these plants might cost and how they could perform in the future. An indicator for studies which model the entire process sequence is the explicit documentation of the final refined outputs (i.e. % of jet fuel, diesel, naphtha, light gases or heat/electricity in the case for FT), which are important metrics in calculating the total product output in energy terms and thereby the energy efficiency.
- Total annual operating hours (i.e. the capacity factor or the annual availability factor) is an important assumption in the normalisation. This is much less of an uncertainty for bio-based systems that are not influenced by the intermittency in renewables. For H2tL and H2tM, the annual availability factor fluctuates between 68 and 91%, aligning with the typical operating hours of electrolysers, with the lower limit established by Tremel et al. [43]. The uncertainty posed by taking the investment cost at face-value in the units of $/GJ is higher for such technologies. For a fair comparison or normalisation, both cost and performance considerations require factoring out the availability factor. This ensures that the capital required for producing a unit of a product remains unaffected by subjective decisions regarding operating hours.
- It is important to recognise that the data extracted here is representative of Nth plant estimates. Albeit most of these technologies do not yet exist, it is unreasonable to apply cost reduction or improvements in the plant performance due to expected learning on these data. The floor costs presented here are likely to be the lowest cost of such plants after several commercial plants have been commissioned. This applies equally to the highest energy efficiencies.

On an individual basis, the scale factor, availability factor, CEPCI/UCCI index, and assumed heating value pose relatively low potential margin for error (calculated by dividing the highest and the lowest extracted values for each parameter), with percentages of 26%, 34%, 30%, and 27%, respectively. Yet in the absence of due diligence in the data interpretation, these potential risks could escalate to a combined 120%.

Lastly, while this study provides evidenced and relatively narrow ranges in the values which could be used for further assessments, it is recommended that extensive sensitivity studies are conducted on the cost and performance of synthetic hydrocarbons production plants, particularly if used as inputs in the field of energy systems modelling [8] as techno-economic optimisation models display penny switching effects [61]. Also, it is advised to adopt a conservative view and sense check futures by considering the most pessimistic views of the techno-economics as those values are typically driven by a sample of reliable studies.

5. Conclusion

With increasing attention on low-carbon fuels and chemicals to meet climate targets, careful cost and performance evaluation becomes critical. FT and methanol synthesis applications hold significance owing to their well-established status and their capacity to process low-carbon feedstocks. The abundant techno-economic data available for these technologies, along with the inherent data variability, poses challenges when utilised for extended assessments or to guide decision-making. Despite numerous sources of variability, the techno-economic characterisation in this work finds that the interquartile ranges for FT and methanol synthesis technologies using biomass or hydrogen with captured CO_2 are relatively narrow, with the outlying data points reasonably understandable given context. The extent to which the spread in the data exist clearly indicate considerable reviews are necessary to obtain a clear outlook of the views of the available data on the cost and performance, highlighting that reliance on a single or a small sample of techno-economic papers could be misrepresentative. The presented comprehensive characterisation of comparable investment costs and plant performances intends to support enhanced representation of synthetic liquid hydrocarbon plants in future studies.

CRediT authorship contribution statement

Seokyoung Kim: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paul E. Dodds:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Isabela Butnar:** Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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Data availability

All data used in the manuscript is available in the Supplementary Material

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Appendix A. Supplementary data

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