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Potentials of Sustainable Aviation Fuel Production from Biomass and Waste: How Australia's Sugar Industry Can Become a Successful Global Example

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Abstract: This study assesses Queensland's sugar industry potential for sustainable aviation fuel (SAF) production via biomass-to-liquids (BtL) processes. Using surplus sugarcane bagasse, preliminary estimates suggest that individual mills could support 60–130 MW_{th} gasifiers, while clustered approaches enable larger capacities. Annual BtL syncrude production could reach 440 mL, increasing to ~1000 mL with additional feedstocks. These findings highlight both the industrial-scale viability of SAF production and the logistical and engineering challenges that must be addressed to align with Australia's renewable energy and fuel security goals.

Keywords: biomass-to-liquid; sustainable aviation fuel; bagasse; gasification

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Academic Editor: Changwei Hu

Received: 17 March 2025
Revised: 27 March 2025
Accepted: 31 March 2025
Published: 2 April 2025

Citation: Dossow, M.; Shadravan, V.; Naim, W.; Fendt, S.; Harris, D.; Spliethoff, H. Potentials of Sustainable Aviation Fuel Production from Biomass and Waste: How Australia's Sugar Industry Can Become a Successful Global Example. *Biomass* **2025**, *5*, 21. https://doi.org/10.3390/biomass5020021

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1. Australia's Energy Transition

Australia's energy transition is guided by the Australian Government's commitment to emissions reduction targets of 43% by 2030 compared to 2005 levels and achieving net-zero emissions by 2050 [1]. Additionally, Australia's National Hydrogen Strategy aims to position the country as a significant player in the global hydrogen industry by 2030 [2]. In the aviation sector, Australia aims to achieve its renewable energy targets by leveraging sustainable aviation fuel (SAF). SAF must meet strict specifications to qualify as a drop-in replacement for conventional jet fuels–complex hydrocarbon mixtures primarily in the C8–C16 range, including paraffins, naphthenes, and aromatics [3]. SAF certification is provided under ASTM D7566 [4] to meet conventional Jet A1 standards as listed in ASTM D1655 [5].

CSIRO's "Flight path to sustainable aviation" report in 2011 identified the opportunity for a local bio-derived jet fuel industry, emphasising the potential availability of sustainable biomass in the region, especially from sources like bagasse [6]. In 2023, the Australian SAF roadmap by CSIRO outlined the importance of SAF in decarbonising the aviation sector [7]. The roadmap highlighted the potential for SAF, with some projections indicating that Australia could produce up to 90% of its jet fuel demand from biogenic feedstocks by 2050 [7]. This trajectory for transition to SAF aligns with global initiatives such as the International Air Transport Association's goal of achieving net-zero emissions by 2050. The report addresses the trade-off between emission reduction potential (based on default lifecycle emissions values sourced from the Carbon Offsetting and Reduction Scheme

for International Aviation (CORSIA) eligible fuels [8]), economic viability, and possible immediate-term implementation [7]. It also emphasised the sovereign capability that a local SAF industry could support, reducing reliance on fuel imports and supporting broader efforts to meet renewable energy targets [7]. Australia has only two oil refineries left in operation after the shutdown of five out of seven refineries over the last fourteen years [9–12]. To encourage energy security, there are several government and industry initiatives in place to support opportunities for the fuels sector to transition to a net-zero emissions trajectory [13,14]. For example, the Queensland Government has partnered with Ampol to assess the feasibility of a biofuels manufacturing plant at Ampol's Lytton site [15–17]. Through its "Queensland's Biofutures 10-Year Roadmap and Action Plan", which was launched in 2016 and refreshed in 2022, the region also intends to create an Asia–Pacific hub in biomanufacturing and biorefining to help diversify Queensland's economy and leverage its strategic advantages [18]. Brisbane Airport has also committed to the World Economic Forum's Clean Skies for Tomorrow initiative, aiming to achieve 10% SAF usage by 2030. The airport is also exploring domestic production opportunities [19]. Qantas Airlines was the second airline in the world to commit to net-zero emissions by 2050, and through its Climate Action Plan, has also committed to using 10% SAF in its overall fuel consumption by 2030 [20]. Furthermore, Jet Zero Australia has formed a consortium including partners such as LanzaJet, Qantas, Airbus, and Idemitsu Kosan to conduct a front-end engineering design study and further project development work to assess the viability of a subsequent commercial-scale alcohol-to-jet (ATJ) production renewable fuels facility [21].

Australia participates in the CORSIA scheme [22] with international sustainability criteria, including land use change. However, unlike the EU's RefuelEU Aviation initiative, it currently lacks domestic mandates, blending quotas, or tax incentives specifically supporting SAF. Especially when it comes to scaling up advanced biofuel SAF production, no domestic plans have been communicated to date [23,24]. However, there are several technological and structural opportunities to develop appropriate value chains for the emerging bioproducts industry in Queensland. Producing sustainable fuels from biomass residues and byproducts from the sugar industry (and other major agricultural sectors) provides an important opportunity to leverage significant existing infrastructure in a well-established industry sector. There are also opportunities for synergistic developments using sugar industry biomass residues in conjunction with other agricultural byproduct feedstocks and, potentially, other waste streams. Key factors in the existing sugar milling industry that influence the development of the BtL industry include understanding the sugar milling process and the characteristics of raw materials, including its infrastructure capacity and the entire value chain from farm to mill and beyond. Given the diverse range of potential technology processes and pathways for producing fuel from bagasse, there is a need to assess the relative merits of these processes, products, and markets to enable appropriate RD&D and commercial demonstration initiatives [25]. This communication paper aims to provide an initial analysis of the relative technical and financial benefits of some of the most promising processing options that could support the efficient utilisation of sugarcane residues, and provide an appropriate platform enabling feedstock consolidation, diversification, and growth of this important emerging sustainable fuels industry.

2. Australia's Sugar Industry

Australia's sugar industry, primarily located in Queensland, is a significant contributor to the nation's economy. As shown in Figure 1, the industry currently operates through nine companies and 22 sugar mills, 19 of which are located in Queensland. In total, these mills process approximately 32.5 million tonnes of sugarcane per year from over 4500 farms.

The industry is a key player in global raw sugar markets, with major export destinations including South Korea, Indonesia, Japan, and Malaysia [26–28].

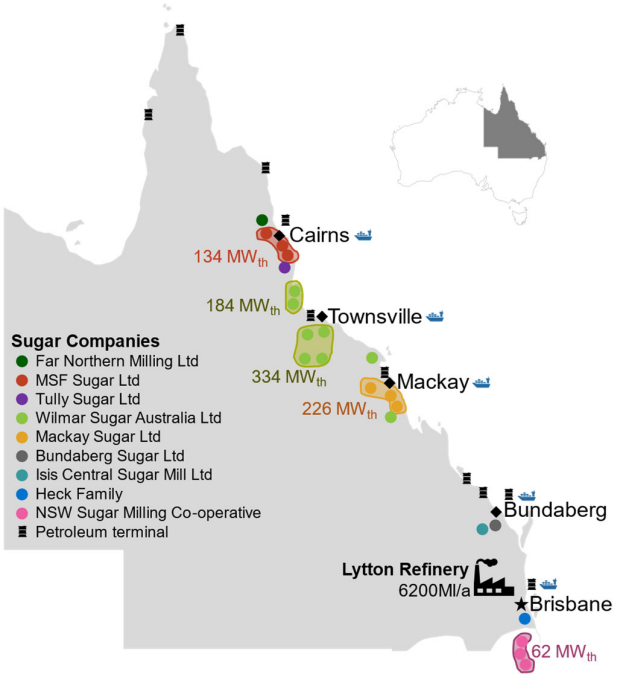


Figure 1. Spatial distribution of sugar mills in Queensland, Australia and possible semi-centralised BtL clusters with corresponding, indicative, gasifier sizes.

Sugarcane is a perennial grass which is cultivated globally in many tropical and subtropical regions [29]. Sugarcane processing is primarily carried out in factories strategically located near sugarcane farming areas to minimise transportation costs. The factories operate seasonally, coinciding with the sugarcane harvesting period, which varies based on climatic and economic factors related to peak sugar content [29]. In Queensland, sugarcane harvesting typically takes place between June and November [30] with sugar processing lasting about 21 [25] to 23 [31] weeks per year. In traditional sugar factories that produce raw sugar as their main product, raw sugar revenues account for more than 95% of total revenues [29].

Sugar factories in Queensland and northern New South Wales collectively produce between 4 and 4.5 Mt of raw sugar each year, with about 85% of the raw sugar produced being exported. Queensland is the second-largest raw sugar exporter globally, and the industry contributes approximately AUD 2.0 billion to Queensland's annual export earnings [27,28]. The industry is exposed to the volatility of the raw sugar world market [32]. Hence, there is a growing interest within the industry to diversify products and value streams where possible. Bagasse, the fibrous cane residue remaining after sugar juice extraction, is identified as a key resource for energy storage and power production and for producing bio-commodities, such as advanced biofuels, which present an opportunity for complementary processes alongside sugar production [25]. From the demand side, the economic viability of biofuel production remains a primary challenge, given that fuel costs contribute significantly to an airline's total operating expenses [3]. Viability of the biofuels pathway is tightly linked to feedstock availability, distribution, handling, and preparation costs, which contribute about 50% of the overall fuel production expenses [3].

The sugar industry presents a unique advantage in this context. The production of sugar at a network of large, central mills yields a highly localised and relatively abundant source of bagasse, well-suited for BtL processes [33]. While the establishment of such

biofuel production processes faces hurdles related to the discontinuous sugar mill operation, infrastructure, and investment barriers, many of the technologies to generate syngas from bagasse and other solid residues, and to process this key intermediate to produce synthetic crude and refined fuels, are well developed in other sectors and are available for adaptation and deployment in this sector. Queensland's sugar industry thus offers promising opportunities as a basis for large-scale biofuel and SAF production.

3. Biomass-to-Liquid (BtL) for the Sugar Industry

The economic viability of bagasse utilisation through BtL hinges not only on the sugar production process but also on a comprehensive understanding of the biomass production, harvesting, and transport system throughout the supply chain. The availability of sugarcane and its residue varies by region and may require preparation, storage, and potential consolidation with other feedstocks to accommodate seasonal fluctuations [25]. In Australia, both road transport and railway systems are employed for the delivery of biomass, including sugarcane and residues. The transportation network for sugarcane is complicated, mainly because the needs of the various harvesting machines at different locations have to be met efficiently, and at the same time, a continuous supply of sugarcane to the mills has to be guaranteed [25,34].

Raw sugar production, as explained in more detail in the ESI, results in large amounts of fibrous residue [35]. This bagasse (see Table 1) is currently predominantly used within the sugar factories. The burning of bagasse produces steam for the milling process and electricity [36]. While such co-generation practices not only ensure energy self-sufficiency for the sugar mills, but in some cases, also supply green electricity to the grid, surplus bio-electricity from bagasse fed to the grid only accounts for around 2% of Queensland's grid electricity mix [37]. Furthermore, most raw sugar factories, including those in Australia, are rather inefficient in terms of steam generation and process energy use [30] as these systems were developed to utilise excess bagasse, which in previous times was a free and abundant resource. Excess bagasse was considered a waste, and there was little incentive to invest in more efficient processing technologies for bagasse utilisation. Even despite the co-generation practices, there exists unused bagasse today that is not fully utilised within the process and is considered waste [30]. This surplus bagasse represents an untapped resource that could be used in BtL applications.

Table 1. Bagasse characteristics derived from [38].

Property	Unit	Values		
		ar	dry	daf
Proximate analysis				
Moisture content	wt%	50.00		
Ash content	wt%	2.90	5.80	
Volatile matter	wt%	39.16	78.33	83.15
Fixed carbon	wt%	7.94	15.87	16.85
Ultimate analysis				
Carbon	wt%	22.09	44.18	46.90
Hydrogen	wt%	2.77	5.53	5.88
Oxygen	wt%	21.81	43.62	46.31
Nitrogen	wt%	0.29	0.57	0.61
Sulphur	wt%	0.05	0.10	0.11
Chlorine	wt%	0.10	0.19	0.20
Gross calorific value				
HHV	MJ/kg	9.46	18.92	20.09

The choice of biomass feedstock in itself raises the question of whether bagasse, surplus bagasse, and/or additional trash and tops from the sugar cane processing chain can be used to enhance economy-of-scale and contribute to the industry's overall viability by creating new revenue streams. The resulting requirements for harvesting practice, in turn, have implications for the value chain, logistics, and BtL process. In addition, other biomass, such as forestry residues, could be used as additional feedstock in BtL plants to achieve the appropriate scale of operations that will be required for an industrial-scale sustainable fuel industry. Following some earlier comprehensive studies of the use of surplus residues for more efficient bio-electricity generation between 2000 and 2010 [25,32,39–41], the Australian sugar industry is now considering additional value-adding processes for bagasse and other harvest residues [33,42–44].

The most common sugarcane-based BtL process globally is the production of second-generation ethanol either directly from molasses sugars via fermentation [29,45] or, in case of bagasse, trash and tops, via ethanol fermentation after enzymatic hydrolysis [46]. A subsequent alcohol to jet (ATJ) process could allow the production of second-generation biofuels. However, lignocellulosic materials do not contain monosaccharides readily available for bioconversion, making the preliminary hydrolysis process necessary [47]. Various technologies are employed in the production of ethanol from sugarcane residues, as explained in the ESI. Such necessary pretreatment steps impose significant technological steps and requirements [46,47] which can increase the cost and complexity of the overall process. The economic viability of the entire process chain is contingent on the existence of a robust ethanol market. The scalability and flexibility of the process for co-processing alternative feedstocks, such as trash, tops, agricultural, and forestry residues, also remain uncertain.

An alternative approach is to use mature thermochemical BtL processes consisting of syngas generation through gasification, followed by syngas conditioning and fuel synthesis [48]. Synthesis options include methanol synthesis followed by Methanol-to-Jet (MtJ, not yet ASTM certified), Fischer–Tropsch Synthesis (FTS) yielding synthetic crude oil (syncrude) that is amenable to further upgrading through mature commercial technology pathways [49], or syngas fermentation yielding ethanol which would then need to be processed via AtJ [50]. To facilitate feedstock consolidation and large-scale gasification operations, there may be a need to include a suitable pretreatment method, such as torrefaction, to increase the energy density and facilitate transportation and storage, prior to syngas generation via a suitable gasification technology or combination of gasification variants [51]. Pressurised oxygen-blown, entrained flow gasification is attractive for large-scale, high-quality syngas production [52]. SAF synthesis from syngas via FTS allows the subsequent upgrading to be conducted in existing oil refineries up to a blending limit of 10% [5]. The produced 'drop-in' SAF allows existing aircraft to be operated without any technical modifications, thus significantly reducing the cost at the system level [53].

Comparative analyses between biological and thermochemical gasification-based synthetic fuel production pathways indicate that the thermochemical pathway demonstrates superior energy efficiency and lower environmental burdens across various impact categories [54,55]. While alternative SAF routes from biomass-derived intermediates such as furfural, HMF, and levulinic acid are being explored [56–58], these remain at low TRLs and lack ASTM certification. In contrast, the thermochemical BtL route offers greater technological maturity, near-term industrial applicability, and leverages existing infrastructure at scale. Based on a comparison of the sustainability and economic criteria of all ASTM-approved SAF production routes, the gasification route appears to be the most promising candidate [3]. Consequently, it is recommended to consider the syngas-based BtL process route. A more detailed analysis of the proposed technological pathway is provided in the ESI.

4. SAF Production Potentials and Costs

Achieving economy of scale in the BtL context requires a significant feedstock supply from feedstock production to harvesting, transportation and conversion technology. Since the development of a successful renewable fuels and chemicals sector depends on both the local availability of renewable biomass feedstocks and the strategic regional placement of processing facilities, the question arises as to whether future bagasse-based BtL plants should be built centralised to leverage the scaling effect, or decentralised to reduce transport distance and costs [29,44,59].

The selection of appropriate BtL plant scale and location requires a comprehensive analysis throughout the entire value chain, encompassing both up- and downstream equipment [60]. With 22 sugar mills concentrating the available surplus bagasse in Australia, the question of optimal BtL plant location is less complex than in other BtL considerations. An analysis of sugar harvesting data is used here to estimate the likely amount of surplus bagasse available as feedstock for syngas production via gasification. To evaluate the approximate gasifier capacity, the amount of available bagasse is estimated for all sugar mills currently operating in Australia. This feedstock availability data is used to assess whether a single mill could theoretically supply an individual gasifier or whether clustering of multiple mills for a central facility is required. The analysis is based on the assumptions listed in Tables S1 and S2 and the harvesting data from the 2022 season [26] as provided in Table S3. These assumptions provide a baseline for evaluating the potential of the BtL process for SAF production.

The estimate indicates that approximately 2.1 Mt of surplus bagasse is currently available in Australia per year, which is consistent with previous estimates [33]. Based on a syncrude yield of 0.17 $kg_{syncrude}/kg_{biomass,dry}$, if all surplus bagasse were to be converted to FT syncrude in BtL plants, this would result in a FT syncrude quantity of about 440 mL/a. The Lytton refinery in Brisbane refines about 6200 mL of crude oil per year (and produces approximately 325 mL/a jet fuel), meeting approximately 9% of Australia's fuel demand [61]. Converting all the surplus bagasse from Australia's sugar industry to syncrude in BtL plants could thus substitute approximately 7% of the Lytton Refinery crude. Assuming that trash and tops could more than double the amount of available biomass feedstock, that capacity could increase to more than 15% (1000 mL/a). If the sugar factories were to reduce (and ultimately cease) using bagasse and instead use other renewable energy sources such as solar and wind, the BtL syncrude production capacity could approach 50% of the Lytton refinery's crude capacity.

Assuming the economic viability of BtL plants based on gasification relies on a gasifier size exceeding 50 MW_{th}, 14 out of the 22 sugar mills examined could potentially support such a facility. Notably, the three largest mills together could surpass the 100 MW_{th} gasifier size. An alternative approach is to group the mills based on their geographical proximity. Such a semi-centralised approach aims to cluster smaller factories, achieving gasifier sizes of over 50 MW_{th}, preferably up to around 100 MW_{th}. The geographical location of sugar mills in Queensland and northern New South Wales favours such clustering, as shown in Figure 1.

In a second step, cost–benefit calculations are conducted. One central torrefaction unit is assumed at the biggest mill, and bagasse from mills with a transport distance of 55 km and 110 km is torrefied at that central location. Bagasse from more distant mills is assumed to be torrefied in the respective, smaller decentralised facilities (see Figures S5 and S6, as well as Tables S4 and S5 for all assumptions based on [40]).

The cost–benefit results in Figure 2 show that this supply chain option is potentially an attractive and practical scenario for all cases with a feedstock transportation distance < 200 km, which is consistent with reasonable transportation distances, and is

also applicable for suitable, practical gasifier sizes. By incorporating the semi-centralised torrefaction assumptions, this estimate indicates gasifier sizes ranging from 98 MW_{th} (when only Mill A supplies biomass) to 255 MW_{th} in the scenario involving five supplying mills. This falls within the gasification plant size range projected in the potential analysis and confirms that these scenarios, involving one to five mills, have a reasonable practical basis.

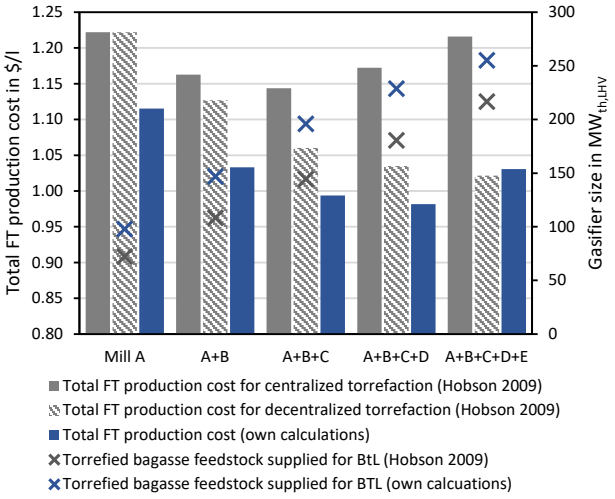


Figure 2. Comparative costs for the road transport of raw or torrefied bagasse and resulting gasifier sizes, based on Hobson 2009 [30] and the current study.

Economically, the estimate appears viable for all cases except when all mills contribute bagasse, showcasing a cost advantage of 10% to 15% compared to centralised torrefaction [40]. For larger gasification scales, decentralised pretreatment eventually becomes more economically viable [40]. Thus, as shown in Figure 2, such clustered sugar factories would be able to supply gasification plants at a reasonable scale. Transport distances are mostly in the range below 100 km and rarely approach 200 km. FT syncrude production at semi-centralised BtL plants, and subsequent transportation to a central refinery, likely Lytton, offers a potentially economically viable scenario.

5. Conclusions

SAF is expected to play a crucial role in decarbonising the global aviation sector by mitigating emissions and other environmental impacts. Australia has an opportunity to develop a domestic SAF industry that leverages existing infrastructure and renewable resources. This study demonstrates that Queensland's sugar industry, with its surplus bagasse, offers a realistic feedstock base for SAF production through biomass-to-liquid (BtL) processes. Among various conversion pathways, gasification-based BtL stands out for its technological maturity, scalability, and compatibility with current refining infrastructure.

The potential analysis conducted here shows that larger sugar mills in Queensland could support a gasification plant of 60–130 MW_{th} by using only already available surplus bagasse. For smaller mills, a more centralised approach is required where up to five mills could supply a single gasifier, resulting in feedstock transport distances in the 100–200 km range. The estimate indicates that, if all 2.1 Mt/a of surplus bagasse available in Australia were to be converted to FT syncrude in BtL plants, approx. 440 mL FT syncrude could be produced annually. Changes in mill operation or harvesting practices could potentially unlock larger quantities of unused bagasse feedstock. Using sugarcane trash and tops, that capacity would increase to about 1000 mL/a for BtL. Economically, the newly established estimate appears viable for transportation distances below 200 km. Being applicable for

suitable gasifier sizes ranging from 100 to 255 MW_{th}, the estimates indicate a potential cost advantage of 10% to 15% compared to previous estimates.

Remaining engineering challenges, especially in biomass-to-syngas processing, syngas cleaning, and adapting technology to the specifics of sugar industry residues, can be addressed by building on existing solutions from other industrial sectors. More detailed, site-specific studies will be needed to refine the assumptions used in this study, particularly regarding seasonal fluctuations, harvesting practices, and mill operation. Enhancing harvesting approaches, such as whole crop harvesting, could substantially increase available biomass but will require careful assessment of impacts on logistics and mill infrastructure.

Overall, by strategically adapting existing supply chains and technologies, Australia's sugar industry could become a cornerstone of a domestic SAF value chain, supporting national goals for fuel security, emissions reduction, and regional economic development.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/biomass5020021/s1, Figure S1: Simplified sugar processing flow diagram from field to raw sugar including the traditional and proposed use of bagasse, trash, and tops in a competing Biomass-to-Liquid process; Figure S2: Feedstock selection, sugarcane harvesting practices and their implications on logistics and the BtL process; Figure S3: Proposed Biomass-to-Liquid (BtL) processes via syngas preparation using gasification followed by either FischerTropsch (FT) synthesis or syngas fermentation and subsequent upgrading options to sustainable aviation fuel (SAF); Figure S4: Simplified flowsheet of the Alcohol-to-Jet pathway to produce SAF from ethanol in accordance with ASTM D7566; Figure S5: Schematic of transport logistics and bagasse torrefaction used for transport cost benefit calculations by Hobson (2009); Figure S6: Schematic of transport logistics and bagasse torrefaction used for novel transport cost benefit calculations based on Hobson (2009); Figure S7: Simplified schematic Biomass-to-Liquid (BtL) process flowsheet, including pretreatment (drying, torrefaction, grinding), oxygen-blown entrained flow gasification, water quench, sour WGS, Selexol® based acid gas removal (AGR) and Fischer–Tropsch synthesis (FTS); Figure S8: Simplified carbon flow simulation results for the BtL model, normalized to pure carbon biomass input; Figure S9: Simplified energy flow simulation results for the BtL base case model, normalized to pure energetic biomass input based on LHV; Table S1: Inputs to storage and transport cost analysis for raw bagasse and TPB per year 13. 11; Table S2: Assumptions for preliminary potential analysis; Table S3: Estimated surplus bagasse and syncrude production potential for sugar mills in Queensland and New South Wales; Table S4: Key inputs and derived outputs for BTL scenarios common to both the raw bagasse and TPB scenarios; Table S5: Key inputs and derived outputs for novel semicentralized BtL scenarios.

Author Contributions: Conceptualisation: M.D. and V.S.; Funding acquisition: H.S.; Investigation: M.D. and V.S.; Methodology: M.D., V.S. and W.N.; Project administration: M.D., V.S. and S.F.; Supervision: D.H., H.S. and S.F.; Visualisation: M.D.; Writing—original draft: M.D.; Writing—review and editing: M.D., V.S., D.H. and S.F. All authors have read and agreed to the published version of the manuscript.

Funding: The authors (Marcel Dossow, Weiss Naim, Sebastian Fendt, and Hartmut Spliethoff) gratefully acknowledge funding of the project "REDEFINE H2E" (01DD21005), sponsored by the German Federal Ministry of Education and Research, as well as financial support by the German Academic Exchange Service (DAAD; German: Deutscher Akademischer Austauschdienst) through their ERA Green Hydrogen Fellowship.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the Supplementary Materials.

Conflicts of Interest: The authors declare no conflicts of interest.

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