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Mapping Residual Biomass and Assessing Low-Carbon Hydrogen Pathways in Sardinia

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ABSTRACT

Residual biomass can support low-carbon hydrogen deployment in Sardinia only when feedstock availability and pathway performance are assessed within a common framework. This work integrates a regional biomass matrix with a harmonized literature-based life-cycle comparison of hydrogen routes relevant to the island. Agricultural residues, livestock by-products, forestry biomass, biodegradable municipal solid waste, dairy residues, and wastewater sludge were screened in terms of actual availability (AA), actual use (AU), potential use for energy (PUE), moisture, and mobilization constraints. Sardinia shows two dominant groups: wet and geographically anchored streams, mainly livestock residues, municipal biowaste, dairy by-products, and wastewater sludge, are better suited to anaerobic digestion (AD), biomethane upgrading, and subsequent reforming because they are already linked to farms, treatment plants, or agro-industrial facilities; conversely, lignocellulosic streams, namely forestry biomass, cereal straw, and pruning residues, are more coherent with thermochemical routes, provided that seasonality, moisture, collection radius, and pre-treatment logistics are controlled. Under a harmonized cradle-to-gate (CTG) convention, gasification (3.7–5.3 kg CO_2e/kg H_2) and AD-derived biomethane reforming (5.0–5.6 kg CO_2e/kg H_2) represent the most mature and regionally transferable options. Overall, the results support a dual regional strategy based on biomethane reforming for wet streams and thermochemical conversion for forestry and pruning residues.

1. INTRODUCTION

Hydrogen is increasingly considered a strategic energy vector for industrial decarbonization, seasonal energy storage, and the defossilization of hard-to-abate sectors. However, the environmental profile of hydrogen is highly sensitive to feedstock origin, conversion route, co-product accounting, and the boundary system adopted for comparison [1-10]. For biomass-based hydrogen, this sensitivity is particularly strong because residual feedstocks differ widely in moisture content, seasonality, spatial concentration, current uses, and logistical constraints. A route that appears favorable in purely process terms may become unattractive when long-haul transport, energy-intensive pre-treatment, or solvent-intensive gas cleaning are considered.

This issue is especially relevant for islands and peripheral regions, where energy planning must simultaneously consider feedstock geography, infrastructure availability, and the possibility of building new industrial chains around local residual resources. Sardinia is a representative case. The island combines an extensive agricultural and livestock base with a significant forestry component, a structured, separate collection system for municipal biowaste, and a distributed network of wastewater treatment plants. At the same time, Sardinia does not offer a single dominant residual biomass; instead, it shows a portfolio of streams that differ in scale, water content, seasonality, and degree of territorial anchoring.

For this reason, the key question is not whether residual biomass can contribute to hydrogen production in Sardinia in generic terms, but which pathway families are technically and environmentally coherent with the residual streams that can actually be mobilized on the island. Answering this question requires the integration of two analytical dimensions that are often treated separately: the regional assessment of feedstock availability and the comparative environmental assessment of conversion routes. The first identifies what resources exist, in what amounts, and under which constraints. The second indicates how those resources perform once converted into hydrogen under comparable life-cycle assumptions.

The present work adopts this integrated perspective. It combines a data collection matrix that presents aggregated information on the main biomass categories within the full territory of Sardinia with a harmonized literature-based life-cycle assessment on hydrogen production routes from residual biomass. The objective is to derive a decision-oriented screening of the hydrogen pathways that are most relevant for Sardinia. The contribution is therefore not a new process simulation or a site-specific optimization study, but a regional synthesis that links feedstock classes, mobilization constraints, and cradle-to-gate (CTG) climate performance within the same framework.

2. MATERIAL AND METHODS

2.1 Regional biomass matrix

The regional biomass matrix was constructed by combining statistical, technical, and bibliographic information for the main residual biomass sectors in Sardinia: agriculture, livestock, forestry, biodegradable municipal solid waste, dairy by-products, and urban wastewater treatment sludge [11-14]. For each feedstock, the analysis distinguished between actual availability (AA), actual use (AU), and potential use for energy (PUE), so as to separate physical generation from the share that can plausibly be mobilized for hydrogen-oriented value chains.

The biomass matrix was calculated by distinguishing three quantities for each biomass type: AA, AU, and PUE. AA represents the annual residual biomass physically generated in Sardinia. PUE represents the share that can realistically be mobilized for energy conversion after accounting for current uses, collection constraints, and sustainability assumptions. AU is calculated as the residual biomass share excluded from this estimated energy potential, as:

$$AU = AA - PUE \quad (1)$$

For agricultural residues, AA was estimated using activity data and residue-generation coefficients according to:

$$AA = AGD \times RC \quad (2)$$

where, AGD is the agricultural activity datum, i.e., harvested production for cereal straw, industrial grape residues, olive residues, and artichoke residues, or cultivated surface for pruning residues, and RC is the crop-specific residue coefficient derived from literature and technical databases. The PUE was then obtained by applying biomass-specific mobilization coefficients [15, 16]. A 70% energy-use coefficient was applied to soft wheat, durum wheat, rye, oat mixtures, barley, corn, sorghum, rice and artichoke residues; 40% to industrial grape residues; 75% to vine pruning and fruit-tree pruning residues; 10% to industrial olive residues; and 65% to olive pruning residues. The remaining share was reported as AU.

For livestock residues, liquid and solid manure were calculated from 2024 herd numbers, average live weight and manure-production coefficients by species and age class as:

$$\text{Liquid manure: } AA = NC \times DUL \times PC \quad (3)$$

$$\text{Solid manure: } AA = NC \times DUS \times PC \quad (4)$$

where, NC is the number of animals, DUL and DUS are the liquid and solid manure production coefficients per unit of live weight, and PC is the average live weight [12, 17, 18]. Mobilization coefficients were then applied to account for collection constraints: only 30% of cattle manure and 50% of pig manure were considered usable for energy purposes, while the remaining fraction was assigned to AU. For the final regional matrix, this corresponds to an effective PUE of 47.8% for liquid manure and 50.8% for solid manure.

For wool and slaughterhouse by-products, AA was estimated from animal production data [17]. For wool, an average greasy-wool production coefficient of 1.2 kg/head was adopted. For slaughterhouse by-products, residues were estimated as the difference between live weight and carcass weight. In both cases, one-third of the annual quantity was assumed to be available for energy use, while two-thirds were assigned to AU.

For dairy residues, whey production was estimated from milk processing, assuming that 80–90 kg of whey are generated per 100 kg of milk processed [17]. Since 40–50% of whey is typically discarded as effluent, a 45% energy-use coefficient was adopted. The remaining 55% was assigned to AU.

For forestry biomass, AA was calculated using forest surface (S), specific utilization coefficients (C_u), average annual volume increments (K), wood density (ρ), the total volume on a wet basis (V), and silvicultural removal coefficients (C_s). Specifically, annual volume was estimated as $S \times C_u \times K$, converted to wet-basis mass using ρ (defined as M_l), and then multiplied by C_s to obtain the net removable mass M_n, which equals AA.

$$V = S \times C_u \times K \quad (5)$$

$$M_l = V \times \rho \quad (6)$$

$$AA = M_n = M_l \times C_s \quad (7)$$

The main silvicultural removal coefficients were 50% for coppice, 15% for high forest, 0% for Mediterranean maquis, 20% for cork oak and chestnut stands, 50% for conifers, and 35% for mixed stands [13, 17, 19-22]. The forestry biomass available for energy was assumed equal to 65% of AA; the remaining 35% was assigned to AU.

For the biodegradable fraction of municipal solid waste (BFMSW), AA was taken from the amount of organic waste already intercepted by separate collection [14]. Since this stream is already collected within the waste-management system, PUE was assumed equal to AA and AU was set to zero.

For urban wastewater treatment sludge, AA was estimated from population equivalent and specific sludge-production factors as:

$$AA = PE \times PF \times 365 \times 10^{-6} \quad (8)$$

where, PE is the served population equivalent, and PF is the specific sludge production factor in g dry matter PE^{-1} day^{-1}. A conservative assumption was adopted by referring to digested sludge rather than raw sludge [14]. Since the whole estimated sludge amount was considered potentially valorizable, PUE was assumed equal to AA and AU was set to zero.

2.2 Harmonized comparison of hydrogen routes

The second methodological block consisted of a harmonized review of literature-based life-cycle assessments of hydrogen from residual biomass. Because the available studies differ in functional unit, system boundary, and co-product treatment, the comparison was brought onto a common CTG basis: 1 kg H_2 at plant gate after pressure swing adsorption (PSA); IPCC 100-year global warming potential (GWP); no credits for exported heat, electricity, oxygen, or digestate substitution; no carbon capture and storage (CCS); and no post-gate compression, distribution, or end use. Under this convention, pathway differences reflect process and supply-chain features rather than accounting choices.

Four route families were retained because they can be plausibly linked to Sardinian residual streams. The first is gasification followed by gas cleaning, water-gas shift (WGS),

and PSA, which is relevant for forestry biomass, cereal residues, and pruning streams [1, 2, 5, 9, 10]. The second is anaerobic digestion (AD) followed by biogas (BG) upgrading to biomethane and subsequent steam methane reforming (SMR), WGS, and PSA, which is relevant for wet residues such as manure, BFMSW, whey, and sludge [3, 4]. The third is steam reforming of bio-intermediates, mainly bio-oil, ethanol, and glycerol, which offers a way to compare secondary thermochemical platforms and logistics-mediating solutions [5, 6]. The fourth is dark fermentation (DF), optionally combined with other biological upgrading steps, which is potentially attractive for selected high-biodegradability substrates but remains less mature at an industrial scale [7, 8, 14].

The harmonized review preserved scenario variants separately from base values. Thus, results including credits, post-gate operations, liquefaction, or CCS were not mixed into the reference comparison. By removing such credits from the baseline, the analysis identifies the climate signal associated with the core pathway itself and then discusses downstream or market-dependent effects as optional scenario deltas. The magnitude of these excluded elements is then reported as scenario deltas relative to the CTG-core values, so that pathway comparison and project-specific design choices remain transparent.

2.3 Feedstock-to-route matching logic

Route matching was not based on life-cycle values alone. A pathway was considered regionally relevant only if it satisfied a coherent combination of feedstock properties, supply-chain characteristics, and technological maturity. Moisture content was one of the first screening criteria. High-moisture streams, especially those above 60–70%, are poorly suited to direct thermochemical conversion unless they are previously dewatered or transformed through an intermediate platform. Conversely, lignocellulosic residues with moderate moisture are more suitable for gasification or pyrolysis, especially where storage and seasonal collection are possible.

Geographical anchoring was a second criterion. Streams already concentrated at treatment facilities or dense livestock districts are more compatible with biochemical platforms, because collection is intrinsic to the system. Dispersed agricultural residues and forestry feedstocks require dedicated collection networks and therefore benefit from solutions that can tolerate seasonal storage or intermediate densification. Finally, maturity and transferability were considered. Even when a route shows favorable climate results on selected substrates, it was not considered a primary regional option if its industrial readiness, scale-up evidence, or substrate flexibility remain limited. This criterion proved especially important for dark fermentation and routes based on microbial electrolysis cells (MECs) [7, 8, 10].

3. RESULTS AND DISCUSSION

Table 1 provides the overall screening of the residual biomass resources available in Sardinia, reporting for each feedstock the AA, AU, PUE, and the average moisture content. This matrix is not intended only as a ranking by gross mass, but as a decision-support tool to identify which biomass streams are both quantitatively relevant and technically coherent with hydrogen-oriented valorization pathways. For this reason, the regional matrix was synthesized into two large feedstock families.

Table 1. Data collection matrix on biomass availability in Sardinia

Biomass Type	AA (ton w.b.)	AU (ton w.b.)	PUE (ton w.b.)	Average Moisture Content (%)
Soft wheat	606	182	424	15
Durum Wheat	107300	32190	75110	15
Rye	66	20	46	15
Oat Mixtures	10408	3122	7286	15
Barley	28613	8584	20029	15
Corn	37253	11176	26077	30
Sorghum	134	40	94	30
Rice	17577	5273	12304	15
Artichoke	85468	25641	59828	90
Industrial Grapes	8056	4834	3222	80
Vine Pruning	76296	19074	57222	45
Industrial Olive Cultivation	31092	27982	3109	50
Olive Pruning	83500	29225	54275	45
Apple	683	171	512	40
Pear	554	139	416	40
Peach	2654	664	1991	40
Nectarine	389	97	292	40
Apricot	372	93	279	40
Plum	658	164	493	40
Liquid Manure	6888460	3594617	3293843	95
Solid Manure*	803451	395217	408234	
Wool	3190	2126	1063	15
Slaughterhouse By-products (White Meat)	3611	2407	1204	70
Slaughterhouse By-products (Red Meat)	33146	22097	11049	65
Dairy products	472507	259879	212628	85
Forestry Sector	414656	145130	269526	50
Biodegradable Fraction of Municipal Solid Waste (BFMSW)	227848	-	227848	60
Urban wastewater treatment sludge*	24341	-	24341	

Notes: w.b. = Wet basis, actual availability (AA), actual use (AU), and potential use for energy (PUE). Biomass marked with * is expressed on a dry weight basis.

The first includes wet and geographically anchored streams, such as liquid manure, solid manure, dairy by-products and whey, the BFMSW, and urban wastewater sludge. These are characterized by high moisture, continuous generation, and strong linkage to farms, treatment plants, or agro-industrial facilities, and suitability for biochemical conversion. The second includes mainly lignocellulosic streams, namely forestry biomass, durum wheat straw, artichoke residues, vine pruning, and olive pruning, which are characterized by lower moisture, stronger seasonality, and greater compatibility with storage and thermochemical processing. This simplified grouping does not replace the detailed matrix but provides a clear decision structure for route matching. Minor residues are retained in Table 1 for completeness, but they are not discussed in detail because of their limited quantities, higher dispersion, stronger competing uses, or lower relevance for regional-scale hydrogen pathway design.

3.1 Wet residual streams as the primary biochemical platform

The regional matrix (Table 1) highlights the first dominant family composed of wet and geographically anchored biomass residue. In gross terms, liquid manure is by far the largest stream. Even after applying mobilization constraints linked to collection efficiency and current management practices, the energy-oriented share remains above 3.29 million t/y on a wet basis. This result is decisive because it shows that the livestock sector, and particularly the districts where collection is already structured, provides a scale of resources that no individual crop residue can match. Solid manure contributes an additional 408,234 t/y on a dry-matter basis, confirming that animal husbandry is the main source of potentially digestible residual biomass in Sardinia.

The significance of this cluster is not only quantitative. Wet livestock residues are also territorially anchored. They arise where animals are reared, and therefore their management already involves local infrastructures, handling routines, and environmental constraints. This is exactly the type of context in which AD becomes attractive: the objective is not to transport diluted biomass to a central thermochemical plant, but to valorize streams near the point of generation and then move a higher-value energy carrier, such as biomethane or hydrogen, further downstream. Therefore, the regional matrix supports the view that wet livestock residues are not just available feedstocks but also structurally compatible with biochemical conversion platforms.

A second strategic component of the wet cluster is represented by BFMSW. The 227,848 t/y on a wet basis identified in the matrix are particularly relevant because they are already intercepted by separate collection and therefore do not require the primary mobilization effort typical of agricultural residues. In practical terms, BFMSW can be directed to AD within existing waste-management systems, and the resulting biogas can then be upgraded and reformed. Relative to agricultural residues, BFMSW offers continuity, centralized handling, and reduced uncertainty in collection, even though contamination control and digestate management remain necessary conditions.

Dairy by-products and whey add another 212,628 t/y on a wet basis. Their relevance is often overlooked if only solid biomass is considered, yet they may constitute one of the most attractive streams for advanced biorefineries because they originate at processing plants, exhibit high biodegradability, and can be integrated with industrial waste-management strategies. In the Sardinian context, where dairy production is strongly rooted in the regional economy, this stream may support hub-scale biochemical conversion at locations where transport penalties remain modest and where hydrogen demand can be coupled with existing food-industry or mobility uses.

Urban wastewater sludge, although smaller in mass terms, contributes a further 24,341 t/y on a dry-matter basis. Sludge is important not because it dominates the regional balance, but because it is strictly tied to wastewater treatment plants and therefore fits a hub logic of territorial concentration. In a regional hydrogen perspective, sludge alone is unlikely to justify dedicated hydrogen facilities. However, it can become a relevant co-feedstock in integrated AD platforms, especially when combined with BFMSW or other wet residues. This points toward a multi-feedstock biochemical architecture rather than a one-residue-one-plant approach.

Taken together, the streams in Table 1 suggest that Sardinia possesses a robust base for AD and biomethane-oriented schemes. Their main constraints are not resource scarcity but methane management, digestate handling, water content, and the need to avoid excessive transport of low-energy-density streams. Accordingly, the regional value of wet biomass lies less in direct hydrogen production at the farm scale and more in the creation of territorial biomethane hubs that can subsequently be reformed under controlled industrial conditions [3, 4, 13, 14].

3.2 Lignocellulosic residues and thermochemical opportunities

The second dominant feedstock family in Sardinia is lignocellulosic and includes forestry biomass, cereal straw, vine pruning, olive pruning, and several agro-industrial by-products (Table 1). Unlike wet residues, these streams are not continuously generated at treatment plants or livestock facilities. They are seasonal, spatially distributed, and often linked to field operations such as pruning or harvest. This implies that their relevance for hydrogen production depends not only on quantity but also on the ability to organize collection windows, intermediate storage, and transport chains without excessive losses or costs.

Forestry biomass is the largest stream in this group, with 269,526 t/y of net extractable biomass after accounting for silvicultural constraints. This figure is especially important because it already reflects a sustainability filter: not all standing biomass can or should be harvested for energy use. Therefore, the forestry estimate provides a realistic ceiling for thermochemical planning. In climate and logistics terms, forestry biomass is also attractive because it can support dedicated gasification platforms at a scale larger than that of most individual agricultural residues. Nevertheless, moisture remains non-negligible, and the energy performance of the route depends strongly on drying strategy, heat integration, and the transport distance between forest extraction areas and conversion sites [9].

Among agricultural residues, durum wheat straw stands out as the most relevant dry feedstock, with 75,110 t/y of potential use on a wet basis and a very high dry-matter share because of its low moisture content. This makes straw a technically favorable thermochemical feedstock. However, its mobilization is constrained by competing uses, especially as bedding or soil-related functions, and by the fragmented

geography of cereal cultivation. As a result, straw is better interpreted as an important complementary feedstock for co-gasification or for district-scale gasification hubs than as the unique basis of a regional hydrogen strategy.

Pruning residues from vines and olive groves are also significant. Their PUE reaches 57,222 and 54,275 t/y on a wet basis, respectively, and both exhibit moisture around 45%, which is much more compatible with thermochemical conversion than the values observed for manure, whey, or sludge. These streams have an additional territorial advantage: they arise in agricultural districts where their seasonality is predictable and where intermediate collection and chipping strategies can be organized. In the Sardinian context, pruning residues are therefore particularly suitable for decentralized pre-treatment followed by centralized gasification or pyrolysis.

Artichoke residues deserve a more cautious interpretation. Their wet-basis quantity is large, but their moisture content is around 90%, so the dry-matter equivalent is only 5,983 t/y. In other words, artichoke residues appear prominent if only wet mass is reported, but they are far less attractive when energy density and drying requirements are considered. This example illustrates why route selection cannot rely on gross terms alone. In practice, artichoke residues may be suitable only under local or co-processing configurations that exploit short transport distances or shared treatment infrastructures.

Overall, the lignocellulosic cluster supports thermochemical platforms more convincingly than biochemical ones. Yet the regional implication is not that all dry biomasses should be fed directly to a single large gasifier. Rather, the matrix suggests a differentiated chain in which forestry biomass may sustain centralized thermochemical hubs, while distributed agricultural residues may benefit from intermediate logistics solutions such as local chipping, densification, or pyrolysis to bio-oil before centralized reforming. This distinction becomes clearer once the harmonized route comparison is considered together with the biomass data [5, 6, 9, 11, 14].

3.3 Harmonized pathway screening and technology ranking

The harmonized CTG GWP ranges for hydrogen pathway families relevant to Sardinia are listed in Table 2. When the literature is aligned under a common CTG convention, gasification of lignocellulosic residues and AD-based biomethane reforming emerge as the two main H_2-valorization routes for Sardinia. Typical gasification cases based on forest residues or lignocellulosic crops cluster around mid-single-digit values. Wulf and Kaltschmitt [1] report 3.7 kg CO_2e/kg H_2 for forest residues and 5.3 kg CO_2e/kg H_2 for short-rotation coppice, while Li et al. [2] report 3.82 kg CO_2e/kg H_2 for corn-straw gasification when only the core CTG blocks are retained. Highly integrated wood-to-hydrogen systems can fall below this range, as shown by Antonini et al. for specific no-CCS configurations, whereas small-scale systems with utility-intensive separations or embedded power-credit issues may rise well above it [9].

Table 2. Harmonized cradle-to-gate (CTG) global warming potential (GWP) ranges for hydrogen pathway families relevant to Sardinia

Route Family	CTG GWP	Dominant Drivers	Regional Relevance
Gasification - WGS - PSA	Typically 3.7–5.3 kg CO_2e/kg H_2	Steam duty, gas cleaning, heat integration, freight	High for forestry and pruning residues
AD - upgrading - SMR - WGS - PSA	5.0–5.6 kg CO2e/kg H_2	Methane slip, digestate handling, electricity	High for manure, BFMSW, whey, sludge
Bio-oil steam reforming	about 3.5–6.5 kg CO_2e/kg H_2	Upstream pyrolysis, steam use, solvent losses	Relevant as a logistics-mediating option
Ethanol steam reforming	2.8–4.0 kg CO_2e/kg H_2	Process integration and a biogenic energy support	Relevant to existing low-carbon energy processes
Glycerol steam reforming	about 7.0–12.0 kg CO_2e/kg H_2	Upstream biodiesel burdens and allocation	Low unless linked to a stable biodiesel chain
Dark fermentation	about 0.79–1.11 kg CO_2e/kg H_2	Substrate quality, gas polishing, scale-up maturity	Promising niche option for selected effluents

Notes: Ranges were derived from the harmonized literature review under a common CTG convention without credits, carbon capture and storage (CCS), or post-gate operations. SMR: steam methane reforming; WGS: Water-gas shift; PSA: Pressure swing adsorption.

The key point is that most gasification cases become regionally meaningful only when utilities and logistics are well controlled. Steam demand, tar and contaminant removal, solvent use, and feedstock freight can dominate the final footprint [1, 2, 5, 9]. This is highly relevant for Sardinia because several lignocellulosic streams are seasonally dispersed. The route can remain attractive, but only if plant siting, pre-treatment, and heat integration are designed around actual biomass geography. In this sense, the life-cycle result does not select a single gasifier design; rather, it identifies the operational levers that a Sardinian implementation would have to control in order to remain at the lower end of the credible range.

The Biogas upgrading to biomethane followed by steam reforming (BG-SMR) family shows a similarly robust performance, with harmonized values around 5.0–5.6 kg CO_2e/kg H_2 [3, 4]. Hajjaji et al. [3] report 5.59 kg CO_2e/kg H_2, and Abawalo et al. [4] report 5.05 kg CO_2e/kg H_2 under comparable credit-free CTG settings. Compared with gasification, the dominant drivers are different. Here, the reformer itself is not the main source of variability, but the biology and agronomy around the digester; methane leakage during digestion and upgrading, as well as digestate handling, become the most influential terms. Electricity also matters, but it is generally secondary relative to methane management. This distinction is crucial for regional planning because it means that the climate competitiveness of AD-based hydrogen depends largely on operational discipline and plant integration rather than on an inherent disadvantage of the route.

While bio-oil reforming lies in a similar corridor to gasification, glycerol reforming is generally less favorable because it inherits upstream burdens and allocation effects from the biodiesel chain. Besides, ethanol benefits from process integration and a biogenic energy backbone, hence its low-end placement [5, 6]. In the Sardinian context, this result is important not because bio-oil reforming should replace

gasification, but because it opens a hybrid strategy. Furthermore, distributed pyrolysis can convert low-density lignocellulosic residues into an energy-dense liquid intermediate, reducing transport penalties before centralized reforming. Thus, bio-oil reforming should be interpreted less as a competing route and more as a logistics-mediating complement to thermochemical hydrogen systems.

Dark fermentation yields the lowest harmonized CTG values on selected substrates, with 1.11 kg CO_2e/kg H_2 for municipal biowaste and 0.79 kg CO_2e/kg H_2 for coffee-processing effluents [7, 8]. These values are scientifically interesting because they demonstrate that very low-carbon biological hydrogen is possible when substrates are highly biodegradable, and utility demand remains limited. However, the same evidence base also indicates that dark fermentation is less mature, more substrate-sensitive, and less transferable at the regional scale than AD-based or thermochemical platforms. Once electro-assisted microbial upgrading is added, electricity demand becomes dominant, and the advantage may erode rapidly [10]. For Sardinia, DF is therefore best interpreted as a niche or pilot pathway rather than as the backbone of regional hydrogen planning.

3.4 Scenario variants and boundary-sensitive deltas

The harmonized values reported in Table 2 represent the credit-free CTG-core baseline. However, several elements excluded from this boundary can substantially modify the final GWP of a specific case. For this reason, scenario variants were expressed as deltas relative to the CTG-core value rather than being merged into the baseline comparison. This approach makes it possible to preserve the intrinsic performance of each pathway while showing the magnitude of boundary-sensitive effects such as co-product credits, downstream operations, liquefaction, CCS, and electro-assisted biological upgrading.

The scenario variant analysis listed in Table 3 shows that boundary choices can shift results by amounts comparable to, or larger than, the differences among pathway families. Co-product credits can reduce reported GWP by about 1–3 kg CO_2e/kg H_2, as shown by the small-scale gasification case with Combined Heat and Power (CHP) export and by ethanol steam reforming with embedded electricity credits [6, 23]. Conversely, downstream operations increase the plant-gate footprint: in the corn-straw gasification case, adding the downstream block raises the result by about +1.6 kg CO_2e/kg H_2 [2]. CCS and liquefaction represent even more structural scenario choices. In wood gasification, Antonini et al. report no-CCS values of 1.68–1.92 kg CO_2e/kg H_2, whereas CCS scenarios become net-negative, around −8 to −17 kg CO_2e/kg H_2 [9]. This confirms the potential of biogenic carbon capture but also shows why CCS should not be included in the baseline: it changes the accounting logic and requires additional infrastructure. Similarly, liquefaction should be treated separately because its electricity demand may add around 10–20 kg CO_2e/kg H_2 under average power mixes, making it a logistics scenario rather than a property of the biomass-to-hydrogen pathway itself. Finally, the scenario deltas clarify the role of process design. In the wheat-straw gasification case of Loy et al. [24], high steam demand, ethylene-glycol use, and freight assumptions lead to a very high footprint, around 90 kg CO_2e/kg H_2; a diagnostic sensitivity with lower solvent make-up and more realistic logistics reduces the value to about 46 kg CO_2e/kg H_2, but the result remains a design outlier. A similar conclusion applies to biological add-ons: dark fermentation can show very low CTG-core values for selected residual substrates, but when microbial electrolysis is added, the result rises to +18 kg CO_2e/kg H_2 for operation only and to more than 50 kg CO_2e/kg H_2 when infrastructure is included [8, 10]. Therefore, electro-assisted routes should be considered only where electricity demand is tightly controlled and supplied by low-carbon power.

Table 3. Scenario variants expressed as deltas relative to cradle-to-gate (CTG)-core values

Scenario Variant	Reference Case	CTG-Core Value	Scenario Value	Delta vs. CTG-Core
Co-product credit from CHP export	Rajabi Hamedani et al. [23]	7.9	5.04	−2.9
Embedded electricity credit in ethanol steam reforming	Rodríguez-Fontalvo et al. [6]	3.40	2.16	−1.24
Post-gate downstream operations	Li et al. [2]	3.82	5.39	+1.57
Liquefaction	Scenario envelope	CTG-core + delivery	/	+10–20
CCS on wood gasification	Antonini et al. [9]	1.68–1.92	−8 to −17	about −10 to −19
High-intensity separation design	Loy et al. [24]	about 90	about 46	−44
DF coupled with MEC	Chen et al. [10]	DF only: about 0.79–1.11	18.8	about +18
MEC including infrastructure	Chen et al. [10]	DF only: about 0.79–1.11	53–58	about +52–57

Note: Combined Heat and Power (CHP), carbon capture and storage (CCS), dark fermentation (DF), microbial electrolysis cell (MEC).

Overall, the scenario deltas do not change the main regional ranking. Gasification and AD-derived biomethane reforming remain the most mature and transferable options for Sardinia, while credits, CCS, liquefaction and electro-assisted upgrading should be evaluated as project-specific additions. For thermochemical routes, the main controllable levers are heating integration, steam demand, gas cleaning, solvent make-up and transport distance. For AD-based routes, methane leakage and digestate management remain the decisive parameters. For biological hydrogen, substrate quality and electricity intensity determine whether the route remains competitive.

3.5 Regional deployment and siting implications

The combined interpretation of biomass availability, pathway performance and scenario deltas supports a dual regional strategy for Sardinia. Wet and geographically anchored residues should be prioritized for biochemical hubs based on AD, biogas upgrading and biomethane reforming. These hubs should be located close to livestock districts, municipal biowaste platforms, wastewater treatment plants and dairy-processing areas, where feedstock collection is already partly embedded in existing management systems. In this case, the main design priority is not drying, but stable co-

digestion, methane containment, upgrading efficiency and controlled digestate management [3, 4].

Lignocellulosic residues require a different siting logic. Forestry biomass, cereal straw and pruning residues are more suitable for thermochemical conversion, but their seasonal and spatially dispersed nature makes collection radius, moisture control and pre-treatment decisive. Where forestry biomass is sufficiently concentrated, centralized gasification may be feasible. Where agricultural residues are more fragmented, a hub-and-spoke model based on local chipping, densification, or distributed pyrolysis followed by centralized reforming may be more robust. This approach can reduce transport penalties and improve supply reliability, especially for pruning residues and other low-density lignocellulosic streams [2, 5, 9].

The scenario deltas reinforce this interpretation. Downstream logistics can add more than 1 kg CO_2e/kg H_2 even in relatively favorable gasification cases [2], while high steam demand, solvent use, and unrealistic freight assumptions can push thermochemical routes far outside the usual 3.7–5.3 kg CO_2e/kg H_2 corridor [24]. Conversely, CCS could improve the climate balance of centralized thermochemical hubs if capture and storage infrastructure became available, but this should be considered as a separate deployment option rather than a baseline assumption [9].

Therefore, regional planning should not rank pathways only by GWP values or gross biomass quantities. It should combine mobilizable feedstock, dry-matter availability, collection constraints, plant scale, proximity to hydrogen demand, and the possibility of controlling the main operational levers identified in Section 3.4. In this sense, Sardinia should be interpreted as a portfolio system: biochemical hubs for wet residues, thermochemical hubs for forestry and pruning residues, and pilot-scale biological hydrogen only for selected high-biodegradability effluents.

3.6 Limitations and next analytical phase

This study should be interpreted as a regional screening rather than a spatially explicit optimization. Biomass quantities were assessed at the regional scale, and pathway performances were derived from harmonized literature data rather than from plant-specific inventories for Sardinia. This approach improves comparability across technologies, but it does not capture local haul distances, district-specific electricity mixes, site-level heat integration, detailed plant economics, or the exact location of future hydrogen demand.

A second limitation is that credits, CCS, liquefaction, and downstream hydrogen logistics were deliberately excluded from the CTG-core baseline. This choice is necessary to compare pathway families under consistent rules, but it also means that the final footprint of a specific project may differ once local markets, infrastructure, and end-use conditions are included. The scenario variant analysis provided boundary-sensitive indications, not definitive site-specific results.

The next analytical step should move from regional screening to hub-level modelling. This should include spatial feedstock clustering, seasonal availability, transport optimization, renewable-electricity supply, methane-leakage control, digestate-management options, heat integration, and proximity to prospective hydrogen users. Each candidate hub should be reported as a CTG-core value plus explicit deltas for credits, downstream logistics, CCS, liquefaction, or electro-assisted upgrading, depending on the configuration considered. This would allow Sardinian hydrogen pathways to be compared not only as generic route families, but as implementable regional supply chains.

4. CONCLUSIONS

Residual biomass can contribute to low-carbon hydrogen deployment in Sardinia only if the availability assessment and pathway assessment are read together. The regional biomass matrix identifies two dominant and complementary feedstock families. Wet and geographically anchored streams - especially liquid manure, solid manure, BFMSW, dairy residues, and wastewater sludge - constitute the strongest basis for biochemical platforms. Lignocellulosic streams - especially forestry biomass, durum wheat straw, and vineyard and olive-grove prunings - constitute the strongest basis for thermochemical platforms.

When hydrogen routes are compared under harmonized CTG assumptions, gasification of lignocellulosic residues and AD-upgrading-SMR emerge as the two most mature and climate-robust pathways for Sardinia. Gasification and bio-oil reforming are suitable where dry biomass can be mobilized with controlled logistics and well-integrated utilities. AD-based biomethane reforming is particularly coherent with the island's wet residual streams and existing treatment infrastructures. Dark fermentation remains scientifically promising but should presently be treated as a niche route for selected effluents rather than as the main regional option.

The overall implication is a dual regional strategy: hydrogen from wet residual streams through AD, upgrading, and reforming; and hydrogen from forestry and pruning residues through thermochemical conversion, potentially supported by intermediate pyrolysis where logistics require it. The next step should consist of spatially explicit hub design, integrating local feedstock clusters, transport optimization, renewable-electricity supply, and proximity to prospective hydrogen demand.

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NOMENCLATURE

AA	Actual availability
AD	Anaerobic digestion
AU	Actual use
AGD	Agricultural activity datum
BFMSW	Biodegradable fraction of municipal solid waste
BG-SMR	Biogas upgrading to biomethane followed by steam reforming
CTG	Cradle-to-gate
DF	Dark fermentation
d.m.	Dry matter
GWP	Global warming potential
MECs	Microbial electrolysis cells
PSA	Pressure swing adsorption
PUE	Potential use for energy
WGS	Water-gas shift
w.b.	Wet basis