

Cereal Straw in Al-Jabal Al-Akhdar, Libya: Gross-Residue Screening and a Conditional CHP Energy Balance

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ABSTRACT

Cereal straw is often presented as a potential energy feedstock before its availability has been established. This study links a gross-residue screen for wheat and barley in Al-Jabal Al-Akhdar, Libya, to a conditional engineering test for biomass combined heat and power (CHP). Mapped areas for 2022-2023, Libya-wide grain-yield proxies for 2022, and published local straw-to-grain observations were combined with stated dry-matter scenarios. The central estimate is 69.35 kt yr⁻¹ of gross dry wheat straw and 2.85 kt yr⁻¹ of barley straw, or 72.20 kt yr⁻¹ combined; the deterministic low and high cases are 44.51 and 97.75 kt yr⁻¹. A separate, explicitly hypothetical boiler-organic Rankine cycle CHP balance uses an effective straw-delivery fraction of 20%, a dry-basis lower heating value of 15 MJ kg⁻¹, 12% net electric efficiency and 60% recoverable thermal efficiency. On the central gross-residue case, these assumptions yield 7.22 GWh yr⁻¹ of net electricity and 18.05 GWh yr⁻¹ of utilized heat if half the recoverable heat is used. A 1 MW net electric target operated for 6,000 full-load hours would require 16.6% of gross dry straw to reach the plant under the same assumptions. Neither the delivery fraction nor fuel and plant performance have been measured locally; the CHP figures are conditional design tests, not forecasts or evidence of project feasibility. The calculation identifies which farm-supply, fuel-quality and heat-demand measurements must precede an engineering feasibility study.

قش الحبوب في الجبل الأخضر - ليبيا: تقدير أولي لإجمالي المخلفات وموازنة الطاقة للتوليد المشترك للحرارة والكهرباء

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المخلص	الكلمات المفتاحية
غالبًا ما يُطرح قش الحبوب بوصفه مادة أولية محتملة لإنتاج الطاقة قبل التحقق من توافره. تربط هذه الدراسة تقديرًا أوليًا لإجمالي مخلفات القمح والشعير في الجبل الأخضر، ليبيا، باختبار هندسي مشروط للتوليد المشترك للحرارة والكهرباء من الكتلة الحيوية (CHP). جُمعت المساحات المستخرجة من خرائط الفترة 2022-2023، ومؤشرات غلة الحبوب على مستوى ليبيا لعام 2022، والمشاهدات المحلية المنشورة لنسبة القش إلى الحبوب، مع سيناريوهات معلنة لكسر المادة الجافة. بلغ التقدير المركزي لإجمالي القش الجاف 69.35 ألف طن سنويًا للقمح و2.85 ألف طن سنويًا للشعير، بإجمالي 72.20 ألف طن سنويًا. وبلغ السيناريوهات الحتميان المنخفض والمرتفع 44.51 و97.75 ألف طن سنويًا. وتستخدم موازنة منفصلة افتراضية صراحةً لمنظومة غلاية ودورة رانكين العضوية للتوليد المشترك كسر توريد فعلي للقش قدره 20%، وقيمة حرارية دنيا على أساس جاف تبلغ 15 ميغاجول/كغ، وكفاءة كهربائية صافية 12%، وكفاءة حرارية قابلة للاسترداد 60%. في حالة إجمالي المخلفات المركزية، تعطي هذه الافتراضات 7.22 غيغاواط ساعة سنويًا من صافي الكهرباء و18.05 غيغاواط ساعة سنويًا من الحرارة المستغلة، عند استخدام نصف الحرارة القابلة للاسترداد. ويتطلب هدف قدرة كهربائية صافية قدرها 1 ميغواط، تعمل 6,000 ساعة حمل كامل سنويًا، وصول 16.6% من إجمالي القش الجاف إلى المحطة وفق الافتراضات نفسها. لم تُقَس محلليًا نسبة التوريد أو خصائص الوقود وأداء المحطة؛ لذا تمثل أرقام التوليد المشترك اختبارات تصميم مشروطة، وليست توقعات أو دليلًا على جدوى المشروع. ويحدد الحساب قياسات الإمداد المزارع وجودة الوقود والطلب على الحرارة التي يجب إجراؤها قبل دراسة الجدوى الهندسية.	قش الحبوب مخلفات المحاصيل إجمالي المخلفات المتولدة التوليد المشترك للحرارة والكهرباء دورة رانكين العضوية إمدادات الكتلة الحيوية

Introduction

The global electricity generation in 2024 reached approximately 30,850 TWh (30.85 PWh), with fossil fuels (coal, gas, oil) providing about 58%, renewables (hydro, wind, solar, bio, geo) around 32%, and nuclear around 10%

[1]. Bioenergy remains the largest source of renewable energy globally, serving multiple sectors: the biopower generation reached 698 TWh; Liquid biofuel consumption climbed to 192 billion liters annually, accounting for roughly 4% of total global transport energy demand, the global biogas

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production reached approximately 1.76 exajoules (EJ), and accounting for 73% of all global renewable heat production [2]. Crop-residue mass and conversion capacity enter an energy assessment at different stages. Straw counted on a field may be needed for feed, grazing or soil protection, while storage and collection further reduce the mass reaching a plant [3]. If a usable fraction is established, a biomass-fired boiler can provide heat to a power cycle while supplying recoverable heat to local users [4]. Estimating electricity or useful heat therefore requires both a mass boundary at the farm and an energy boundary at the conversion plant.

Here lies an example in which the collected data can be considered informative yet insufficient. Firstly, a map for 2022-2023 with information about cereal lands has been produced, while some local experiments have been conducted with grain and straw yield data available for wheat and barley [5,8]. The map itself does not have any data about yield of the mapped lands, whereas experiments do not include all the treatments and genotypes. Thus, a national yield estimate may link them for initial testing purposes.

There is a second gap between straw production and engineering use. Without local measurements of competing uses, soil-retention requirements, collection losses, fuel composition and heat demand, a gross-residue total cannot be converted into a verified combined heat and power (CHP) supply. The present study therefore retains gross straw as its evidence-based output and asks a conditional design question: what fraction would have to reach a CHP plant for a specified electrical duty?

Literature synthesis and research gap

While existing Libyan energy research deals with relevant links in the chain, no research deals with the entire crop-specific chain boundaries. The former one gives a comprehensive view of the renewable energy resources in Libya along with barriers to their implementation [9], and the latter describes biomass utilization along with separation of fuel supply from useful output [10]. None of them presents a gross balance of wheat/barley straw for Al-Jabal Al-Akhdar, nor evaluates the effect of delivery fraction on design target.

The Misrata case study incorporates cereal residue into a broader group of municipal and organic feedstocks in hydrogen studies [11]. The study differs from the current one in purpose and spatial scale. With regard to the solid fuel chain, literature evidence on biomass CHP provides information on boiler-powered cycle and the significance of plant size and heat use [4]. This information is useful when setting the conversion boundary; however, it does not provide local fuel tests or straw quantifications.

The available literature on the issue is placed against the context of the research question in Table 1. Figure 1 distinguishes the resource calculation from the conditional engineering calculation. The significance of this work lies in the clear link that is established between the mapped cereal area, the declared yield of grain as a proxy, observations made regarding the straw to grain ratio and the effective delivery ratio for a defined CHP load.

The differentiation between gross straw production and the feedstock quantity which is potentially available is made in Figure 2. The right side reflects agricultural uses, soil retention requirements, and harvesting losses which cannot be quantified. It is used only hypothetically to carry out the CHP calculation in the following sections of the paper.

The goals of this analysis are fivefold: (i) develop proxies for grain production of individual crops using mapped area and country yields; (ii) establish ratios of straw to grain from documented local experiments; (iii) provide minimum, median and maximum gross dry residue estimates; (iv) employ a conditional boiler-organic Rankine cycle (ORC) CHP balance to convert the assumed supply into net electricity, useful heat and a reverse feedstock demand; and (v) determine the measurements required to substitute the engineering estimates with local data.

Materials and methods

Study scope and accounting boundary

The study area comprises mapped wheat and barley fields in Al-Jabal Al-Akhdar. The main boundary in accounting is gross amount of straw produced on the field prior to any

Table 1: Evidence used for cereal-residue screening and the conditional CHP calculation.

Study and scale	Evidence or question	Contribution	Limitation for the present case	Ref.
Crop map	Wheat and barley mapped area, Libya, 2022-2023	Provides a recent spatial basis for crop-specific regional screening	Mapped area does not establish local yield, straw generation, or residue fate	[5]
Wheat trial	Wheat grain and straw yields under field treatments	Supports locally derived straw-to-grain ratios	Trial treatments and seasons do not represent a probability sample of regional farms	[7]
Barley trial	Performance of barley genotypes in Al-Jabal Al-Akhdar	Provides local genotype-level grain and straw evidence	The trial range is not a validated regional distribution	[6]
Libya review	Renewable-energy resources, costs, and implementability	Places biomass within national energy-planning and deployment constraints	Does not quantify a subregional wheat/barley residue balance	[8]
Value-chain review	Anaerobic digestion, upgrading, utilization, and integration	Clarifies downstream conversion and system-boundary requirements	Does not estimate local cereal-residue availability	[9]
Misrata case	Hydrogen potential from mixed solid and organic waste streams, including cereal residues	Documents a Libyan multi-feedstock bioenergy scenario	Feedstocks are aggregated; crop-specific gross and recoverable residue are not separated	[11]
Biomass CHP report	Power cycles, electric efficiency, and useful heat	Defines a plausible conversion architecture and energy-balance boundary	Neither straw quality nor CHP performance is verified for the district	[4]

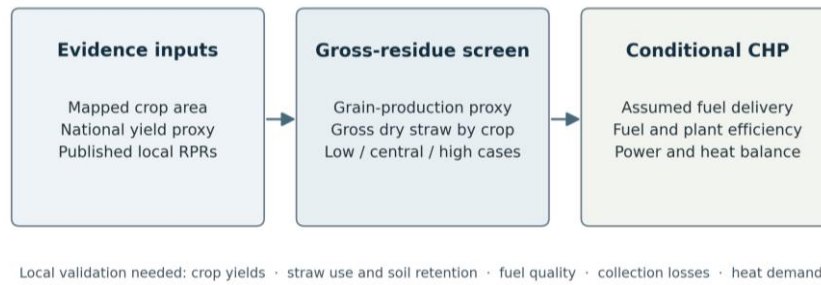


Figure 1: Evidence chain and boundaries of the gross-residue screen and conditional CHP design test.

deductions for grazing, feeding, conservation, or collection losses. The secondary boundary for a CHP system starts from a certain amount of dry straw received by a plant and ends up with net amounts of electricity and heat that are consumed by an identified consumer.

Data sources and evidence status

Crop areas: based on map 2022-2023; national grain yields proxy data: based on national data of 2022; local straw:grain

ratio based on earlier experiment seasons. The inputs above do not refer to the same fields in one harvest season. Table 2 categorizes the observations, national proxy data and sensitivity inputs determined by the analyst. National yields are calculated from production and area-harvested statistics [9]. This should be documented prior to submission.

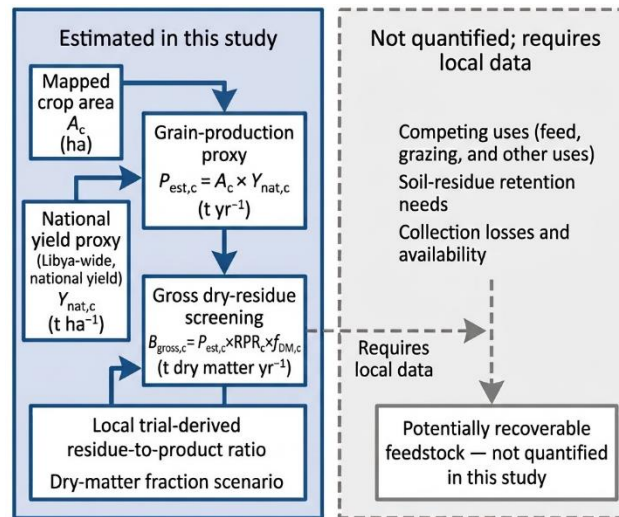


Figure 2: Conceptual workflow for screening gross dry residues from wheat and barley production in Al-Jabal Al-Akhdar, Libya. Crop production is estimated from mapped crop area and national yield statistics, while gross dry-residue generation is screened using the estimated production, residue-to-product ratio, and dry-matter fraction. Local feed use, soil-retention requirements, and collection losses are identified as additional data needed to quantify potentially recoverable feedstock.

Table 2: Inputs and evidence status. Scenario endpoints communicate sensitivity and are not statistical confidence limits.

Input	Value used	Evidence and limitation	Ref.
Mapped wheat area	30,017 ha	FAO 2022-2023 crop map; mapped crop area, not a farm survey	[5]
Mapped barley area	3,606 ha	FAO 2022-2023 crop map	
National yield proxy	Wheat 0.7656; barley 0.508 t ha ⁻¹	2022 national production ÷ harvested area; direct FAOSTAT export needs archival verification	[12]
Wheat straw:grain ratio	2.66 / 3.55 / 4.18	Low / mean / high ratios calculated from paired local trial treatment means	[7]
Barley straw:grain ratio	1.34 / 1.83 / 3.73	Low / median / high ratios calculated from reported local genotype means	[6]
Dry-matter fraction	0.70 / 0.85 / 0.95	Analyst-defined low / central / high scenarios; not measured local moisture	-

Grain-production proxy

The grain-production proxy for crop *c* was obtained by multiplying mapped area by the 2022 national yield proxy (Eq. 1). The multiplication purposefully involves a sub-national scale with a national output [12]. This is a clear estimate of scale yet should not be viewed as an observed output from Al-Jabal Al-Akhdar.

$$P_{est,c} = A_c \times Y_{nat,c} \quad (1)$$

The units for the variables in Eq. (1) are such that the mapped area is in hectares, yield index in tons/hectare, and grain output in tons per year.

Local residue-to-product ratios

The ratio of residues to products (RPR) was obtained for each of the paired observations made during field trials, as straw yield to grain yield (Eq. 2). The wheat RPRs were estimated from the December-January treatment seasons provided and their respective minimum and maximum values determine the ends and their average, the midpoint. For barley, genotype-

level ratios were summarized by their minimum, median and maximum. These choices retain variation observed in the published experiments without presenting a small trial set as a regional probability distribution.

$$RPR_{c,j} = S_{c,j} / G_{c,j} \quad (2)$$

The numerator and denominator in Eq. (2) are paired straw and grain yields for crop c under treatment or genotype j , expressed in the same mass-per-area units.

Gross dry-residue screening estimate

Eq. (3) translates the grain production proxy into gross mass of dry residue by using an assumed RPR and dry matter fraction. Moisture content for each type of crop was not available, and, therefore, 0.70, 0.85, and 0.95 dry matter fractions have been considered for low, moderate, and high sensitivities. The endpoints combine selected parameter values; they are not statistical confidence limits.

$$B_{gross,c} = P_{est,c} \times RPR_c \times f_{DM,c} \quad (3)$$

Gross residue is reported as tons of dry matter per year. The dry-matter fraction is dimensionless. This calculation includes all straw implied by the chosen production proxy and ratio; it makes no deduction for on-farm use, soil retention or losses during collection.

Boundary between gross residue and recoverable supply

The supplied MATLAB model also contains an accounting extension for recoverable biomass. In that extension, gross residue is reduced by assumed shares for livestock feed, soil retention and other uses, then multiplied by a collection fraction (Eq. 4). The equation defines the additional data required; it does not make those fractions locally observed [13].

$$B_{candidate,c} = B_{gross,c} \times \max[0, 1 - f_{feed,c} - f_{soil,c} - f_{other,c}] \times f_{collect,c} \quad (4)$$

Eqs. (1)-(3) provide the resource-screening results. Eq. (4) defines an additional supply balance, but the use and collection fractions in the supplied MATLAB demonstration CSV are hypothetical rather than locally observed. Its simulated surplus and energy percentiles are not reported as district supply. Eq. (5) defines a fuel-energy quantity for a candidate dry feedstock; without a measured lower heating value (LHV), it remains conditional [14-17].

$$E_{feedstock,c} = B_{candidate,c} \times LHV_c / 3.6 \quad (5)$$

In Eq. (5), the feedstock candidate is in units of t dry matter yr^{-1} while the LHV is in MJ kg^{-1} ; dividing by 3.6 gives units of MWh yr^{-1} . This is a chemical energy equivalent and not electrical. The losses in the plant, along with lack of a heat user, necessitates power and heat calculation separately.

Scenario design and reproducibility

The low, central and high results in Table 3 combine selected RPR and dry-matter values. They show sensitivity to those inputs, not sampling confidence intervals. Although the MATLAB script can sample triangular distributions, its use and collection shares are demonstration values and cannot establish a probability distribution for Libyan feedstock supply. Reproducing the gross screen requires the national yield extraction and published trial calculations; validating the engineering balance requires farm yields, competing-use fractions, straw fuel analyses and process data.

Conditional biomass CHP design test

A direct-combustion boiler supplying an ORC unit and a heat-recovery connection is used as a reference architecture, not as an optimized plant design [17]. Let $B_{gross,total}$ be the sum of the crop-specific central gross dry masses in Table 3. The effective delivery fraction f_{eff} groups existing uses, soil retention, collection and storage losses into the share of gross dry straw that could actually reach the CHP boundary. No local value of f_{eff} has been observed. For a transparent test, 10%, 20% and 30% are explored solely as hypothetical inputs:

$$B_{del} = f_{eff} \cdot B_{gross,tot} \quad (6)$$

B_{del} is delivered dry straw (t yr^{-1}). For the two crops, the same f_{eff} and dry-basis LHV are used to keep the example interpretable; measured crop-specific values could be summed instead. The illustrative LHV_d is 15 MJ kg^{-1} . A non-Libyan fuel database reports a measured dry-basis value of 17.65 MJ kg^{-1} for one wheat-straw sample; its value is not transferred to local straw [18]. The 15 MJ kg^{-1} assumption is a sensitivity anchor rather than a district fuel test.

The net electric and potentially useful heat balances are, respectively,

$$W_{net} = \eta_{el} \cdot B_{del} \cdot LHV_d / 3.6 \quad (7)$$

$$Q_{use} = u \cdot \eta_{th} \cdot B_{del} \cdot LHV_d / 3.6 \quad (8)$$

W_{net} and Q_{use} are annual MWh of net electricity and heat actually used; η_{el} includes on-site electric auxiliaries, η_{th} is heat recoverable at a fixed CHP operating point, and u is the fraction of that heat absorbed by a real heat load. The test assigns $\eta_{el} = 0.12$, $\eta_{th} = 0.60$ and $u = 0.50$; these are analyst assumptions, not validated straw-CHP efficiencies. Their sum when $u = 1$ is 0.72, within published general CHP efficiency ranges [17]. Actual power-to-heat trade-offs, fuel moisture, seasonal heat demand and parasitic loads require a plant-specific model. For a target net electric rating P_t (MW) and H equivalent full-load hours per year, Eq. (7) can instead be solved for the minimum effective delivery fraction:

$$f_{req} = \frac{3.6 \cdot P_t \cdot H}{\eta_{el} \cdot LHV_d \cdot B_{gross,tot}} \quad (9)$$

The exemplary power obligation is 1 MW net electric for 6,000 hours full load per year. Eq. (9) considers only the annual mass balance condition, and without a seasonal schedule and storage system, cannot verify continuous operation. The heat requirement has been assumed independent of the electrical generation from the given combined heat and power plant; a change in any of these parameters would necessitate a new efficiency pair.

Results

Crop area and estimated grain production

The crop map estimates 30,017 ha of wheat and 3,606 ha of barley in Al-Jabal Al-Akhdar [5]. Applying the national yield proxies shown in Table 2 results in an annual production of 22,981 tons of wheat and 1,832 tons of barley. This is an estimated production proxy not a harvested amount from the district.

Trial-derived residue ratios

The ratio of paired wheat observations falls between 2.66 and 4.18, and the arithmetic mean is 3.55. Ratios of barley genotype observation fall within 1.34 and 3.73, and the median is 1.83. The wider relative spread observed in barley

is carried forward into the gross residue cases, yet both experiments fail to mention the frequency of such ratios.

Gross dry-residue scenarios

The gross generation of dry-residue material from the chosen scenarios is presented in Table 3 below. It stands at 69,345 t yr⁻¹ for wheat and 2,849 t yr⁻¹ for barley, adding up to 72,195 t yr⁻¹. These amounts lie within the limits of 44,509 t yr⁻¹ (low) and 97,749 t yr⁻¹ (high). The major share in this residue (about 96%) belongs to wheat as it occupies more mapped area than barley.

Table 3: Gross dry-residue screening estimates. Low and high values combine the selected RPR and dry-matter endpoints; they are scenario bounds, not confidence intervals. Combined totals use unrounded crop estimates; displayed rounded components can differ from a total by 1 t.

Crop	Grain proxy (t yr ⁻¹)	Low gross residue	Central gross residue	High gross residue
Wheat	22,981	42,791	69,345	91,258
Barley	1,832	1,718	2,849	6,491
Combined	24,813	44,509	72,195	97,749

Conditional CHP supply and energy balance

Table 4 uses Eqs. (6) - (8) on the gross residue only. With 20% effectiveness, 14,439 t dry straw yr⁻¹ would pass across the plant boundary. Considering the LHV, this equals 60,163 MWh yr⁻¹ of chemical energy. The specified performance pair gives 7,220 MWh yr⁻¹ of net electricity and 36,098 MWh

yr⁻¹ of recoverable heat; only 18,049 MWh yr⁻¹ counts as used heat at $u = 0.50$. None of these masses or outputs has been observed locally.

Table 4 assumes $LHV_d = 15 \text{ MJ kg}^{-1}$, $\eta_{el} = 0.12$, $\eta_{th} = 0.60$ and $u = 0.50$ in every row. Under the same assumptions, Eq. (9) gives $f_{req} = 16.6\%$ for 1 MW net at 6,000 full-load hours. If only the low or high gross-residue cases in Table 3 were changed, the required fraction would be 27.0% or 12.3%, respectively; these values are deterministic input sensitivities.

Table 4: Conditional CHP calculations using the central gross dry-straw screen. All delivery, fuel and conversion parameters are hypothetical; outputs are not forecast production.

Effective delivery	Delivered dry straw (t yr ⁻¹)	Fuel energy (MWh yr ⁻¹)	Net electricity (MWh yr ⁻¹)	Heat used (MWh yr ⁻¹)
10%	7,220	30,081	3,610	9,024
20%	14,439	60,163	7,220	18,049
30%	21,659	90,244	10,829	27,073

Figure 3 shows that the delivery requirement also depends on net electrical efficiency. At the central gross-residue and fuel-energy assumptions, an 8%, 12% or 16% net efficiency would require, respectively, 24.9%, 16.6% or 12.5% effective delivery to meet the same 1 MW annual duty. These are not confidence bounds. No local demand curve or collection schedule has been matched to the assumed 6,000-hour duty.

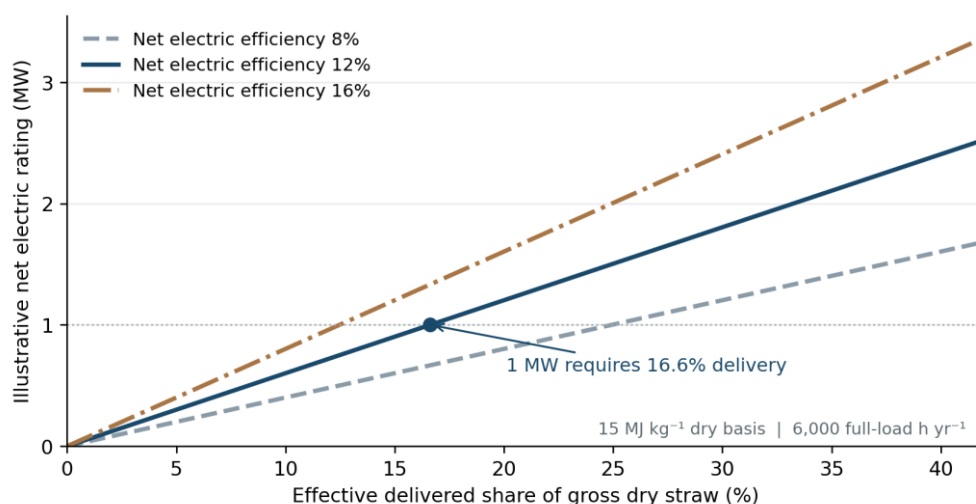


Figure 3: Conditional net electric rating versus effective delivery of the central gross dry-straw estimate for three assumed net efficiencies. All curves use $LHV_d = 15 \text{ MJ kg}^{-1}$ and 6,000 full-load hours per year; the marker shows the 1 MW duty at 12% net efficiency. The plot does not verify plant fuel supply.

Discussion

Interpretation of the gross-residue estimates

The central value of 72.20 kt yr⁻¹ represents the order of magnitude of gross production of straw, according to the selected information. It can serve to guide collection of additional field data but cannot be used to define the amount of plant material to be processed. This is illustrated in Figure 2; straw consumed by agriculture or necessary for the soil cannot automatically be considered delivered fuel.

Wheat constitutes the central value in Table 3, owing to the fact that its area, national yield proxy, and RPR are greater than those of barley. The multiplicative approach transmits the potential bias of the national yield proxy directly to the

calculation of straw. Barley has a lower central value but wider RPR ends.

What the CHP calculation adds

The opposite analysis defines the resource gap through engineering specifications rather than assuming that all gross straw is used as fuel. Based on the central case, the representative 1 MW electric load requires around 12,000 t dry straw supply per year (16.6% of gross straw), which means that it requires an average of 2 t of straw per hour when running for 6,000 full load hours annually. In this case, the corresponding heat input must be assigned to a year-round or seasonally matched load; otherwise, the 50% efficiency level is just an assumption rather than an achieved

one. With regard to the straw-fired boilers, the analysis of ash, alkali and chlorine content must also take place before the equipment choice due to ash deposition and corrosion limitation [18].

Limits to recoverable bioenergy supply

Gross straw production says little about how much could leave the farm. Straw may be fed to livestock, grazed or left to protect the soil; losses occur during collection and storage [3]. Suitable removal limits depend on local soil, slope and erosion exposure. No local survey establishes these deductions for the mapped fields. The delivery fractions in Table 4 therefore serve only to test how an engineering calculation responds to an unknown supply parameter.

Nor does a specified delivery fraction establish that the straw can be burned reliably. Local moisture, ash composition, chlorine, potassium and ash-fusion behaviour affect boiler operation, fouling and corrosion [19]. The assumed LHV and paired CHP efficiencies in Section 3.8 describe one illustrative operating point; heat output counts as useful only to the extent that an actual consumer can take it. Consequently, Figure 3 cannot be used to claim a viable plant, an annual power forecast or a comparison with conventional generation.

Uncertainty and evidence limitations

The main screen on resources separates the ratio of mapped areas versus trials published and the ratio of national yields versus the dry matter fractions. The biggest problem here is whether the national yield can be assumed to apply to the mapped areas. This gap cannot be filled by more Monte Carlo runs, or through the use of small field trials to create the distribution of the RPR for the district. The CHP screen introduces uncertainties related to effective delivery, LHV dry basis, plant efficiency, and heat utilization.

Priorities for local validation

The following test will quantify grain and straw yields at mapped sites in the same season and document straw utilization, soil coverage, harvesting losses, and storage conditions. Testing of fuel will quantify its moisture content, lower heating value, ash content and ash fusion characteristics. Validation through engineering analysis will then require a suggested harvesting radius, actual boiler and ORC performance, electric energy consumption, operating time and local heat load profiles. This would enable turning the assumptions on the delivery fraction and efficiencies into testable variables.

Conclusions

Mapped cereal areas, national yield proxies and local trial ratios produce a central gross dry-straw screen of 69.35 kt yr⁻¹ for wheat and 2.85 kt yr⁻¹ for barley in Al-Jabal Al-Akhdar. The combined central value is 72.20 kt yr⁻¹, with deterministic low and high scenarios of 44.51 and 97.75 kt yr⁻¹. These are not measurements of a single district harvest, and they do not establish sustainably recoverable feedstock.

A conditional CHP balance makes the engineering implication explicit. If 20% of the central gross dry straw were delivered to a boiler-ORC CHP plant, a 15 MJ kg⁻¹ dry-basis LHV and assumed 12% net electric efficiency would imply 7.22 GWh yr⁻¹ of electricity. At 60% recoverable thermal efficiency and 50% heat uptake, useful heat would be 18.05 GWh yr⁻¹. Conversely, a 1 MW net electric duty at 6,000 full-load hours would require 16.6% effective straw delivery under the same assumptions. These figures are conditional design calculations, not predicted output or evidence of a feasible CHP facility. Farm-level straw

allocation, fuel quality and heat demand must be measured before plant sizing or economic and environmental claims can be defended.

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