

DESIGN CRITERIA AND COMBUSTION ANALYSIS FOR A 10 KW TLUD REACTOR

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Abstract: *This paper presents the theoretical background and the main design elements for Top-Lit Up Draft (TLUD) burners, aimed at producing cleaner thermal energy from biomass and reducing emissions associated with incomplete combustion. The key stages of biomass conversion (drying, pyrolysis, oxidation) are described, together with the conditions for complete combustion and the role of stoichiometric air and excess air in controlling CO and particulate emissions. Draft (chimney effect) and flue-gas analysis are discussed as optimization tools for safe operation and higher overall efficiency. The applied section proposes a sizing algorithm for a 10 kW TLUD reactor operating in batch mode for about 3.5 h, starting from a specific reactor power of ~300 kW/m² and a standardized diameter of 0.20 m. For pellets, an initial fuel charge of ~9.42 kg and a gasified biomass rate of ~2.67 kg/h are estimated, corresponding to an available energy of ~160 MJ. The air supply is split into primary (~70%) and secondary (~30%) streams, with indicative flows of about 18 m³/h and 8 m³/h, respectively, to support complete combustion of the produced gas. Overall, TLUD technology is highlighted as an efficient, low-emission option for biomass-based heating applications, including the co-production of biochar.*

Keywords: *TLUD (Top-Lit UpDraft), biomass micro-gasification, reactor sizing; low emissions (CO, PM)*

1. Introduction

The adverse impacts of biomass use for energy production mainly stem from incomplete combustion and the release of CO₂ and particulate matter (PM) into the atmosphere, which contribute to global temperature rise and aggravated climate change. Climate change mitigation and the conservation of forest resources have been major drivers behind many improved-combustion system projects. From an energy perspective, direct burning of woody fuels to generate heat often exhibits significant inefficiencies and should be replaced with modernized combustion systems with higher efficiency and lower pollution.

In many developing countries, traditional open fires are still used for cooking, often with energy efficiencies below 10%. This can be substantially improved by using enhanced combustion devices, thereby reducing firewood consumption and, implicitly, uncontrolled deforestation. Top-Lit UpDraft (TLUD) burners belong to this category of improved systems because they enable staged combustion and finer control of combustion air [1].

Combustion is the reaction of a fuel with oxygen from the air that releases heat. This process is used daily in households for heating and cooking and in industry to generate heat or steam. Combustion accounts for roughly 85% of the world's energy use and is vital to modern life.

In the current context—where emissions reduction, higher energy efficiency, and sustainable biomass utilization are pursued simultaneously—TLUD systems are of particular interest because they can provide low-emission thermal energy and, at the same time, produce biochar with potential for carbon storage. The aim of this paper is to present the sizing elements for a 10 kW TLUD reactor, starting from combustion principles and natural-draft flow fundamentals, and to illustrate the relationship between design parameters and the energetic and environmental performance of the system.

2. Combustion Mechanism

To convert solid biomass into useful thermal energy, it must undergo combustion. Although many different combustion systems are available, the fundamental principle of biomass combustion is essentially the same in each case. There are three main stages of the combustion process, as shown in studies by specialists from the University of Arkansas and the United States Department of Agriculture.

Main stages of the combustion process

1. **Drying** — All biomass contains moisture, which must be removed before combustion can proceed. The heat for drying is supplied by radiation from the flame and heat stored in the combustion chamber. No chemical decomposition occurs in this stage—only phase change from liquid water to vapor.
2. **Pyrolysis** — When the temperature of dried biomass reaches approximately 200–350°C, volatile compounds are released. Pyrolysis products include carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄) and heavier compounds (tar) that may condense upon cooling. These gases mix with oxygen and burn, producing a yellow flame. The remaining solid, after volatiles have been released, is char (biochar). Oxygen must be supplied to sustain the gas-phase combustion.
3. **Oxidation** — At around 800°C, fixed carbon oxidizes (burns). Oxygen is required both in the fuel bed and above it, where CO can further oxidize to CO₂. Adequate residence time in the combustion zone supports complete burnout. In practice, all stages may occur simultaneously in different zones of the combustion chamber.

Combustion is considered complete when the fuel's chemical energy is extracted to the greatest extent and conversion to CO₂ and H₂O is maximized. Achieving as complete a combustion as possible improves fuel utilization and reduces pollutant emissions. Sufficient air must be present, while excess air should be controlled to avoid increased losses with flue gases [2].

Air Requirement for Complete Combustion

Complete combustion occurs when fuel and air are mixed for a sufficient time under adequate turbulence and temperature. Biomass can be approximated chemically as CH₂O. As an example, consider the combustion of 30 kg of biomass. For complete combustion, approximately 32 kg of oxygen are required, along with about 105.3 kg of nitrogen from the air (air contains roughly 21% oxygen and 79% nitrogen by volume). The total required air mass is therefore about 32 + 105.3 = 137.3 kg, i.e., approximately 4.58 kg of air per 1 kg of perfectly dry biomass (0% moisture).

Besides heat, this reaction produces about 18 kg of water vapor, 44 kg of CO₂ (a greenhouse gas), and 105.3 kg of nitrogen. Exact values depend on the actual biomass composition (carbon, hydrogen, oxygen content and moisture), which is why detailed burner design often uses elemental analysis.

Stoichiometric combustion represents the theoretical optimal fuel–air ratio. In practice, it cannot be perfectly achieved due to imperfect mixing, cold zones, and limited residence time. Therefore, additional air—known as excess air—is supplied.

Typical excess-air levels for combustion systems range from 5% to 50%, depending on fuel and system configuration. For TLUD burners, an excess air ratio corresponding to approximately 40–50% can help achieve stable operation with low CO and PM, particularly when the produced gas is burned in a well-mixed burner (e.g., FLOX-type) [3].

Combustion Efficiency

Combustion efficiency depends on how completely the fuel burns and how much of its chemical energy is converted into useful heat. While 100% efficiency is theoretically possible, it cannot be reached in practice due to heat losses (through walls, flue gases, radiation, and convection) and localized incomplete combustion.

Typical combustion-efficiency values are:

- Open fireplace: 10–30%;
- Conventional space heater/stove: 50–80%;
- Commercial gas boiler: 70–82%;

- Residential gas boiler: 70–82%;
- Oil- burner heating system: 73–85%;
- Induced- draft furnace: 74–80%;
- Gas-burner boiler: 75–85%;
- Condensing furnace (gas or oil): 85–93%.

Combustion is a chemical reaction that involves various substances (mainly C, H, and O) and oxygen, producing light and heat as forms of energy. The luminous energy appears in the form of a flame, but most of the energy is released as thermal energy. In the design of biomass burners, including TLUD systems, the emphasis is on increasing the overall thermal efficiency of the system (combustion + heat transfer) and on reducing pollutant emissions.

Complete vs. Incomplete Combustion

Complete combustion occurs when a controlled excess of oxygen is available. Under near-ideal conditions, the fuel mainly produces CO₂ and H₂O, with very low CO and volatile organic compounds. Incomplete combustion occurs when oxygen is insufficient or mixing is non-uniform. In that case, products may include CO along with CO₂, water vapor, and sometimes unburned carbon particles (soot). Incomplete combustion causes energy losses and negative impacts on the environment and health.

Although flame color can sometimes indicate the presence of certain species, the main goal in TLUD operation is to minimize incomplete combustion and maximize both energy efficiency and biochar quality [4].

Draft (Chimney Effect)

Draft refers to the gas flow through the combustion system, from air intake to flue-gas exhaust through the chimney. After combustion, hot gases leave the combustion chamber, pass heat exchangers, and exit through the stack.

Depending on the design of the combustion system, draft can be:

- **natural**, in which combustion air is drawn in due to the density difference between the hot gases and the outside air;
- **mechanical**, when air is pushed or pulled through the system by a fan;
- **combined**, when both the natural draft effect and assist fans are used.

The flow rate of gases from the combustion chamber must be carefully controlled to ensure that all flue gases are removed from the combustion zone at the correct velocity. Insufficient draft leads to a buildup of toxic gases (CO) and potentially explosive gases, such as hydrogen–air mixtures, which may form in the combustion chamber or be vented indoors, creating health hazards.

By contrast, excessive draft can cause unwanted turbulence in the system, preventing complete combustion (the flame is “pulled” out of its optimal zone) and increasing heat losses through the flue gases. High draft is also undesirable because it tends to mechanically overstress the combustion chamber and the heat exchanger.

In TLUD reactor design, chimney height, the indoor–outdoor temperature difference, and pressure losses along the flow path are critical parameters for achieving sufficient natural draft, especially in fan-less configurations.

Combustion Analysis and Key Indicators

Combustion analysis involves monitoring the gases leaving the system after combustion (flue gases) in order to improve the overall process. It is important to monitor flue-gas composition for three main reasons:

- **Environmental concerns** — regular flue-gas testing ensures compliance with environmental standards imposed by national and European legislation.
- **Maintenance and safety** — high concentrations of toxic gases or soot may indicate that equipment maintenance is required (e.g., cleaning heat exchangers, adjusting the burner) to reduce toxic compounds and deposits.
- **Energy efficiency** — the presence of compounds such as carbon monoxide (CO) or high levels of residual oxygen indicates that the combustion process could operate more efficiently, saving fuel and reducing costs.

Combustion analysis typically includes measuring:

- volumetric concentrations of O₂, CO, and CO₂;
- flue-gas temperature;
- chimney pressure or draft.

When oxygen (O₂) is found in the flue-gas exhaust at high levels, it usually means that more air than necessary has been supplied (high excess air), which increases heat losses. When too little oxygen is supplied to the burner, carbon monoxide (CO)—a highly toxic gas—forms in the flue gases, and combustion efficiency decreases [5].

An optimal operating regime for a TLUD gasifier is one in which excess air is sufficient to keep CO below the limits imposed by regulations, but not so high that it significantly penalizes thermal efficiency.

Sizing Elements for TLUD Stoves with Biochar Co-Production

When carbon storage in biochar is desired, sizing calculations determine the reactor diameter and height for a target biochar yield. Biochar composition is useful because it enables calculation of stoichiometric air demand and the regulated (actual) air flow.

Sizing is based on thermodynamics and natural-draft flow principles. Air for gasification is kept below stoichiometric demand to maintain a gasification regime (not direct full combustion of biomass). The total air is split into **primary** and **secondary** flows in typical ratios (e.g., 9:1 or 7:3), depending on geometry and application goals [6].

The reactor diameter (D) is selected so that the maximum gas velocity is on the order of 1 m/s, to avoid entrainment of ash and to ensure a stable flame.

Chimney height (H) can be estimated to provide sufficient natural draft, using:

$$q = CA \sqrt{2gH \frac{T_i - T_e}{T_e}} \quad (1)$$

where:

- (q) = flue-gas flow rate (m³/s),
- (A) = chimney cross-section (m²),
- (C) = discharge coefficient (-),
- (g) = gravitational acceleration (m/s²),
- (H) = chimney height (m),
- (T_i) = average gas temperature in the chimney (K),
- (T_e) = outdoor temperature (K).

Reactor height is set according to the fuel-bed height and the required volume for combustion and post-combustion so that the pyrolysis front advances steadily and produced gases are completely oxidized.

3. General Initial Data on TLUD Gasifiers

Operating principle

A functional scheme of a TLUD gasifier with an integrated burner is typically used. The micro-gasification process is supplied with air either by a variable-speed fan or, in some configurations, by natural draft only. In certain designs, the burner is separated from the reactor. The produced gas (producer gas) has a relatively low heating value, and efficient combustion is supported by specialized burners (e.g., FLOX-type) that provide intense mixing [7].

Biomass is loaded into the reactor and rests on a grate through which gasification air flows upward. Ignition starts from the top of the fuel bed (top-lit).

In most cases, thermal energy is obtained by burning the hot producer gas generated during pyrolysis. The gas mixes with preheated combustion air introduced through ports near the top of the reactor. With strong turbulence, the mixture burns at the reactor outlet at temperatures typically around 900–1000°C.

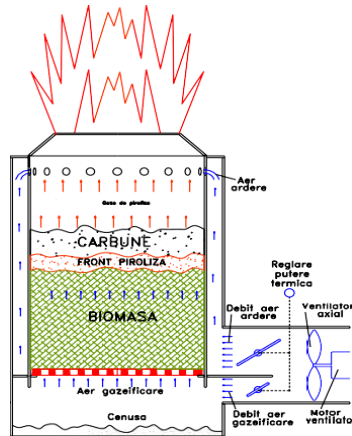


Fig. 1. Functional scheme of a TLUD gasifier with a coupled burner [8]

Output power is controlled by adjusting the gasification air flow (D_{ag}) and the combustion air flow (D_{ard}), either via mechanically linked dampers or by fan speed control. TLUD systems are fixed-bed and operate in batch mode, requiring reloading after the fuel is consumed.

Micro-gasification proceeds at relatively low intensity, with specific hourly fuel consumption of about 80–150 kg biomass/m²·h, leading to reactor specific powers of 250–350 kW/m². The slow process keeps the superficial gas velocity very low ($v_{sup} \leq 0.06$ m/s), which reduces ash entrainment and can yield very low PM_{2.5} concentrations at the burner outlet (reported values on the order of ≤ 5 mg/MJ_{bm}), significantly below many regulatory limits.

Because producer gas and combustion air can be mixed very effectively, at an optimal excess-air ratio of roughly 1.4–1.5, CO in flue gases can be kept very low (reported as <2% or about 0.8 g/MJ_{bm}), depending on conditions and measurement basis. These features make TLUD thermal generators among the least polluting solid-fuel heat-production options.

Figure 2 compares CO and PM emissions for different combustion technologies; TLUD gasifiers typically show substantially lower values than many conventional systems and can fall below common limit values (e.g., sources such as drtlud.com documentation) [9].

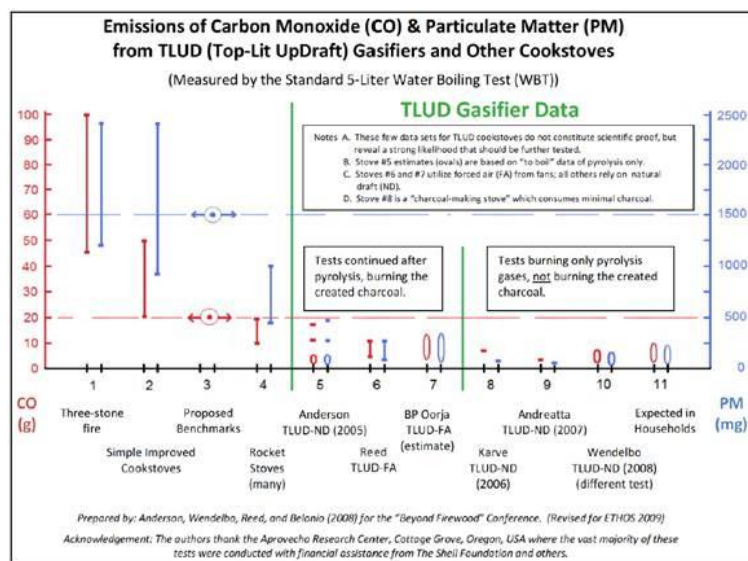


Fig 2. Comparison of CO and PM emissions from different combustion technologies and systems

Gasification stages (drying, pyrolysis, oxidation, reduction) occur simultaneously in different zones of the reactor.

- **Drying** is required because biomass moisture content typically ranges from 5% to 55%. Above 100°C, water is removed as vapor without chemical decomposition.
- **Pyrolysis** occurs roughly between 150–700°C and is the thermal decomposition of biomass in the absence of oxygen.
- **Oxidation** takes place with the help of air introduced into the oxidation zone. Air contains oxygen, water vapor, and inert gases (nitrogen, argon), of which only oxygen actively participates in combustion. Oxidation occurs at 700–2000°C.
- **Reduction** occurs at about 800–1000°C in oxygen-depleted conditions and includes reactions (e.g., Boudouard, water-gas) that generate syngas/producer gas.

Combustible gas components typically include CO (15–30%), H₂ (10–20%), and CH₄ (2–4%), while non-combustible components include N₂ (45–60%), H₂O (6–8%), and CO₂ (5–15%). Exact composition depends on biomass type, temperature, and air–fuel ratio [10].

4. Sizing calculation for a 10 kW TLUD Reactor

Consider a TLUD gasifier with a nominal thermal output of about 10 kW and a batch operating time of 3.5 h.

If the reactor specific power is approximately 300 kW/m², then the required reactor cross-section is: $A \approx 10/300 = 0.033 \text{ m}^2$.

Choose a standardized reactor diameter of $D = 0.20 \text{ m}$, giving:

$$S_r = \frac{\pi \cdot D_r^2}{4} = \frac{\pi \cdot 0.2^2}{4} = \frac{0.19625}{4} = 0.0314 \text{ m}^2.$$

Sizing algorithm for the 10 kW reactor:

- **Reactor diameter: $D = 0.20 \text{ m}$**
- **Reactor cross-diameter: $S_r = 0.0314 \text{ m}^2$**
- Biomass bed height (fuel charge height): $H_{rbm} = 0.5 \text{ m}$
Assume pellet bulk density: 600 kg/m³ (pellets).

The required initial fuel mass (derived below): $M_{bmo} = 600 \cdot 0.0157 = 9.42 \text{ kg}$.

Biomass volume : $V_{rbm} = H_{rbm} \cdot S_r = 0.5 \cdot 0.0314 = 0.0157 \text{ m}^3$

Initial mass in the reactor: $M_{bmo} = 600 \cdot 0.0157 = 9.42 \text{ kg}$

Specific hourly gasified biomass consumption is taken as 85 kg/m²·h; therefore, for the chosen cross-section:

$$C_{hbm} = 85 \cdot 0.0314 = 2.669 \text{ kg/h}$$

Operating time: $T_f = \frac{9.42}{2.669} = 3.53 \text{ h}$

Energy in the gasified biomass:

$$E_{bmg} = M_{bmo} \cdot P_{Cibm} = 9.42 \cdot 17 = 160.14 \text{ MJ}$$

Average thermal power in the hot gases:

$$P_g = \frac{E_{bmg}}{T_f \cdot 3.6} \cdot \eta_{gTLUD} = \frac{160.14 \cdot 0.93}{3.53 \cdot 3.6} = 11.719 \text{ kWth}$$

Useful thermal power at the burner, considering producer-gas combustion efficiency ($\eta_{burn} = 0.95$) and insulation efficiency $\eta_{insul} = 0.96$, will be:

$$P_{burn} = P_g \cdot \eta_{burn} \cdot \eta_{insul} = 11.719 \cdot 0.95 \cdot 0.96 = 10.68 \text{ kWth}$$

This is close to the 10 kW target, with a small margin to accommodate additional losses and fuel-quality variations.

Combustion Air Requirement

The combustion-air demand is estimated for complete combustion with a chosen excess-air level. Indicative values are:

- **Theoretical air** : $\sim 6.5 \text{ m}^3 \text{ air/kg biomass}$
Actual air (with excess): $\sim 9\text{-}10 \text{ m}^3 \text{ air/kg}$

For $M_{bmo} \approx 9.42 \text{ kg}$, the total actual air volume is:

$$V_{air,tot} \approx 9.7 \cdot 9.42 \approx 91 \text{ m}^3 \text{ aer}$$

Average air flow rate:

$$V_{air,med} = \frac{V_{air,tot}}{t_f} \approx \frac{91}{3.5} \approx 26 \frac{\text{m}^3}{\text{h}}$$

This is split between primary and secondary air in an approximate 70%/30% ratio:

- Primary air $\approx 18 \text{ m}^3/\text{h}$
- Secondary air $\approx 8 \text{ m}^3/\text{h}$

Such a split supports complete combustion of the produced gas while keeping CO low, as typically reported for TLUD technology [11,12].

Figure 3 shows the theoretical temperature evolution in the combustion chamber of the 10 kW TLUD burner, with an autonomy of 3.5 h. The following can be observed:

- **Start-up phase (0–30 min)**: a rapid temperature rise to approximately 700°C , as the pyrolysis front forms and producer gas begins to be generated in sufficient quantities.
- **Stable operating phase (30–150 min)**: the temperature remains around 720°C , with small fluctuations, characteristic of a quasi-steady regime.
- **Shut-down phase (150–210 min)**: a gradual temperature decrease toward 100°C , as the biomass is depleted and the process transitions from gasification to biochar cooling.

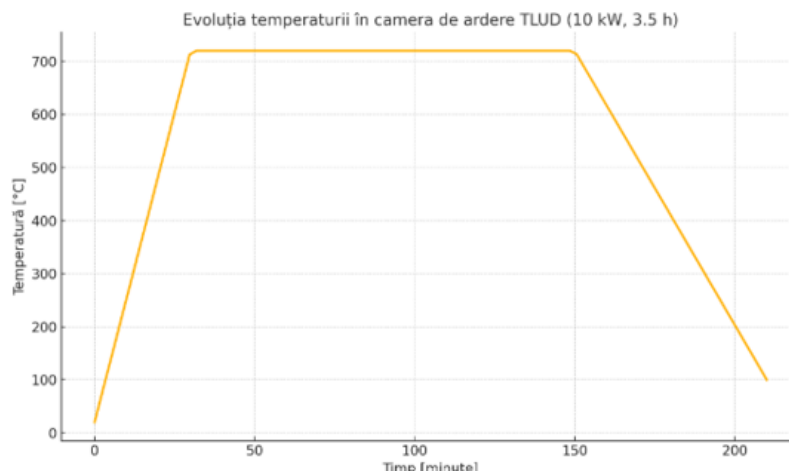


Fig. 3. Theoretical temperature evolution in the combustion chamber of a 10 kW TLUD

Figure 4 shows the evolution of oxygen concentration and airflow rate in the TLUD system. The oxygen concentration in the flue gases changes as follows:

- it decreases from 21% (atmospheric air) to approximately 16% during the complete-combustion phase;
- it stabilizes during the optimal operating phase (30–150 min), indicating efficient combustion;
- it increases again toward the end, signaling fuel depletion and a higher relative share of unused air.

The total supplied airflow rate:

- increases gradually to about $25\text{--}26 \text{ m}^3/\text{h}$ to sustain stable combustion;
- remains nearly constant in steady operation, ensuring complete combustion;
- decreases gradually during the shut-down phase to avoid excessive cooling of the combustion zone and to limit cold-air infiltration into the chimney.

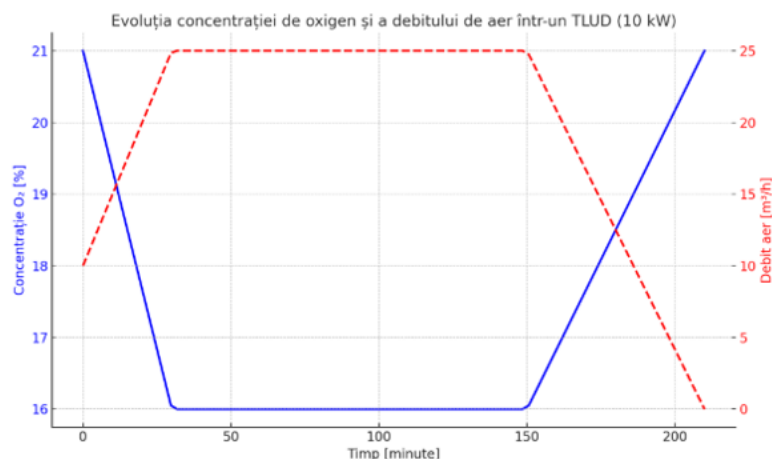


Fig. 4. Evolution of oxygen concentration and air flow in a TLUD system

5. Conclusions

The most important benefit offered by a TLUD-based hot-air generator is that it delivers relatively “clean” thermal energy compared with most other biomass-combustion methods. The equipment is simple and reliable and allows the use of a wide variety of chipped biomass dried to below 20% moisture, while also providing an environmental protection solution by keeping PM and CO emissions below the limits required by regulations.

The sizing calculations presented for a TLUD reactor of approximately 10 kW indicate:

- a cross-sectional area of about 0.0314 m² (diameter 0.20 m),
- a biomass bed (fuel charge) height of about 0.5 m,
- an hourly biomass consumption of approximately 2.7 kg/h,
- an operating time of about 3.5 h in batch mode,
- a useful thermal output at the burner of approximately 11–12 kW, depending on the system’s actual efficiencies.

According to the scientific literature, the TLUD gasification process features a slow advance of the pyrolysis front, with a specific hourly biomass consumption of 80–150 kg/m²·h, which leads to relatively low reactor-specific power of 250–350 kW/m². The slow process keeps the superficial gas velocity in the reactor at very low values ($v \leq 0.06$ m/s) and prevents the entrainment of free ash particles larger than PM_{2.5}, achieving values of up to 5 mg/MJ_{bm} at the burner outlet; this is at least five times lower than the current standards required for solid-fuel heat generators.

From an energy-policy perspective, better organization of the agricultural sector is needed to increase bioenergy production in Romania. Such organization involves:

- coordination and information exchange based on examples of implemented projects;
- establishing a dedicated biomass information point;
- implementing pilot projects;
- creating functional markets and a biomass trading platform.

A comprehensive bioenergy strategy is required for Romania to clarify aspects related to markets, target groups, and priority technologies (including TLUD micro-gasifiers for rural applications). The strategy must set clear objectives and coordinate individual actions so that national and EU targets can be achieved.

In addition, legislative and organizational measures need to be adopted to reduce pollution, greenhouse-gas emissions, and dependence on crude-oil imports, which are increasingly expensive and uncertain, as oil is on a path toward depletion. One solution is to use biomass resources to produce solid biofuels (firewood, pellets, and wood chips), liquid biofuels (ethanol, biodiesel, and crude vegetable oil), and gaseous biofuels (biogas, TLUD producer gas).

It is also necessary to resume and intensify research on the cultivation and industrialization of energy crops (for example, sweet sorghum, rapeseed, and other fast-growing species, including aquatic

plants), as well as to develop robust micro-gasification technologies that can efficiently valorize these resources while simultaneously producing biochar with a role in carbon sequestration.

Acknowledgments

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