Advanced Combustion Control in a Coal-Fired Power Plant Using Air and Fuel Sensing Technologies

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Abstract

Optimizing the stoichiometric air-fuel ratio (λ) is crucial for enhancing combustion efficiency and reducing emissions in combustion-driven power plants in general and in coal-fired power plants specifically. At ISKEN Sugözü Power Plant (ISKEN) in Turkey, EUtech's advanced measurement technologies were implemented to achieve a precise, real-time determination of λ at both the individual burners and boiler levels, enabling data-driven combustion optimization. The EUsoft Air system, a virtual sensor technology, was permanently installed to continuously monitor and analyze the distribution of primary, secondary, and tertiary airflows to each burner of both 685 MW_{el} units under all operating conditions. Additionally, the EUcoalflow mobile system provides accurate data on fuel mass flow distribution within all the burner pipes of a mill. By integrating data from both systems into the plant's DCS, a real-time, spatially resolved map of λ was generated, enabling precise control over local and overall combustion stoichiometry. This approach allows plant operators to identify air-fuel imbalances, fine-tune burner operation, and optimize overall boiler performance. This study highlights the transformative role of real-time virtual sensing and advanced measurement technologies in power plant optimization. Through enhanced burner balancing and automated control, ISKEN Sugözü Power Plant can achieve more stable, efficient, and environmentally sustainable operations, marking a major advancement in combustion monitoring and optimization for coal-fired power plants.

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1. Introduction

Lambda mapping, the spatially and temporally resolved determination of the air-fuel equivalence ratio (λ) at each burner and combustion stage, forms the central innovation in ISKEN Sugözü Power Plant's combustion optimization strategy. By enabling direct visualization and control of local stoichiometry in real time, lambda mapping provides actionable insight that is unattainable with conventional, aggregate instrumentation. This is especially important at ISKEN Sugözü Power Plant (ISKEN), which, commissioned in the early 2000s near Yumurtalik in Adana province, Turkey, stands among the largest privately financed coal-fired power stations in the country, with an installed capacity of 2×685 MW_e. [1]

The plant was developed as a joint venture between STEAG GmbH and OYAK, but as of July 2025, ownership has fully transferred to OYAK following OYAK's recent acquisition of STEAG's shares. [2] The plant is designed for high reliability, efficiency, emissions compliance, and unit availability under demanding and variable grid conditions, a commitment reflected in its ongoing investment in advanced diagnostic, monitoring, and control systems.

ISKEN's latest improvement program, in partnership with EUtech [3], aims for comprehensive assessment and optimization of the combustion process by implementing a high-resolution, real-time methodology for lambda mapping. This approach leverages online diagnostics and advanced data analytics to yield precise air-fuel equivalence ratios where they matter most. In practice, most coal-fired plants, including both legacy and contemporary facilities, do not

possess direct, burner-resolved instrumentation for either air or fuel. [4] While total fuel flow may be measured at the mill and main air flows are typically monitored, the downstream distribution to individual burners and to secondary and overfire air ducts is not measured but merely presumed to reflect design intent. [5] Due to the structural design of the windbox in many plants, it is often physically impossible to install air flow sensors at the burner level, as the complex geometry and internal constraints of the windbox preclude direct measurement. As units age, as operating regimes fluctuate, or as modifications accumulate, these assumptions become unreliable and can give rise to significant and undetected deviations in local air-fuel ratio, which impede both operational flexibility and emissions control. [6] To resolve this limitation, ISKEN has, for the first time in its operational regime, introduced a dual-measurement paradigm, combining continuous virtual sensing of airflow (EUsoft Air) with periodic, non-intrusive coal mass-flow measurement (EUcoalflow mobile). Lambda mapping produced by these integrated systems offers direct, spatially resolved determination of air and fuel distribution at each burner and air duct, enabling targeted, data-driven adjustment of operating parameters to optimize local λ under real boiler conditions.



Figure 1: ISKEN Sugözü Power Plant

2. Theoretical Background

2.1. Stoichiometric Air-Fuel Ratio λ

The stoichiometric air-fuel ratio, commonly denoted by λ (lambda), quantifies the actual amount of air supplied to a combustion process relative to the exact theoretical requirement for

complete combustion. A value of $\lambda = 1$ indicates that the supplied air precisely matches the stoichiometric demand; $\lambda < 1$ corresponds to a fuel-rich condition (insufficient air), and $\lambda > 1$ indicates a fuel-lean condition (excess air). In pulverized-coal combustion, maintaining λ within a narrow band at each burner is critical for maximizing thermal efficiency and minimizing unburned carbon and pollutant formation. [7]

$$\lambda = \frac{\dot{m}_{air}}{\dot{m}_{air,stoich}} \quad (1)$$

2.2. Air Staging in Coal-Fired Power Plants

The implementation of air staging in coal-fired boilers is fundamentally governed by spatially and temporally resolved management of combustion air streams to optimize flame chemistry, pollutant formation, and burnout completeness within the furnace. [8] Air staging operates by systematically partitioning the total combustion air into primary, secondary, and overfire (tertiary) air streams, each introduced at distinct locations and in precise proportions relative to fuel input and local combustion progress. Figure 2 displays the core principle of air staging. The process begins with the delivery of primary air, which entrains and conveys pulverized coal into the burner register, providing the initial oxidant for ignition and initial devolatilization reactions. Secondary air is then supplied coaxially or tangentially at the burner front but is deliberately limited to create a sub-stoichiometric, fuel-rich zone ($\lambda < 1$) at the point of flame stabilization. This engineered oxygen deficiency moderates local flame temperatures and restricts the extent of thermal NO_x production by constraining peak reaction zones to conditions less conducive to nitrogen oxidation. [9] Completion of combustion is achieved through overfire air (OFA) injection, administered via dedicated nozzles or ports at elevations above the primary combustion region. The OFA stream supplies the deficit oxidant needed to drive residual volatile and char oxidation to completion, restoring overall stoichiometry ($\lambda > 1$) at downstream locations while maintaining the requisite turbulence for efficient mixing. The spatial and quantitative disposition of these staged air streams is calculated to sustain adequate residence time for fuel burnout before flue gas heat recovery, preventing the formation of unburned carbon and secondary reductive species such as CO. [10]

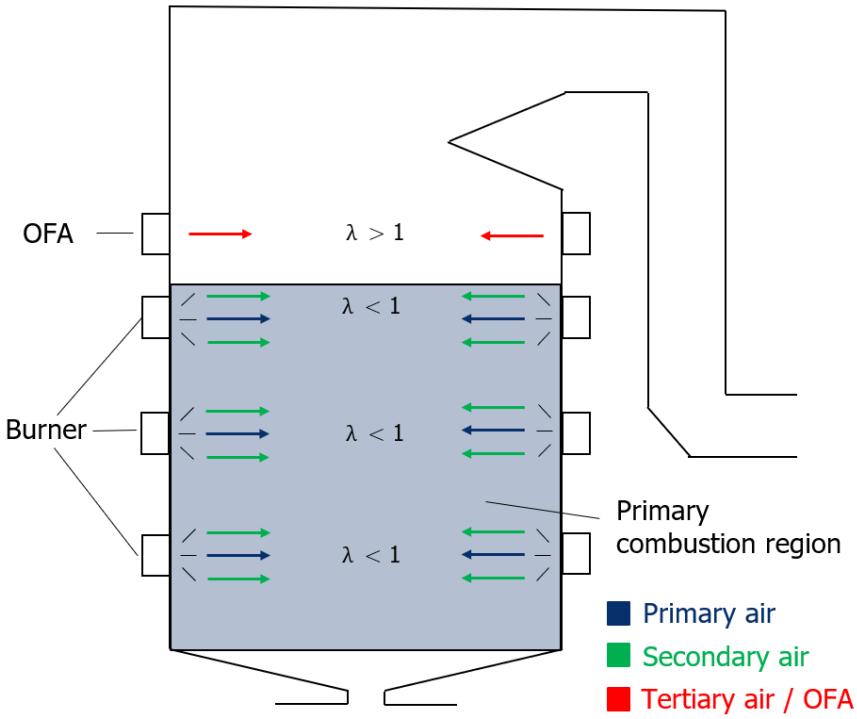


Figure 2: Principle of air staging. Air staging supplies primary, secondary, and over-fire air at separate points during combustion to optimize efficiency and reduce emissions.

2.3. Combustion Hygiene in Coal-Fired Power Plants

Combustion hygiene refers to the ability of the boiler to sustain favorable combustion conditions in both space and time, keeping the global air-fuel equivalence ratio (λ_{ges}) as close as possible to its optimal value (λ_{opt}) and avoiding undesirable fluctuations that could compromise performance. [11] Good combustion hygiene is characterized by a well-balanced distribution of fuel and air, allowing the local λ in each zone to follow the intended air staging profile without creating uncontrolled oxygen deficiencies or excessively oxidizing pockets. Process stability is equally important: fluctuations in fuel feed, air supply, or burner operation can cause temporary departures from the optimal λ, leading to increased CO formation, higher unburned carbon losses, or spikes in NO_x emissions. As illustrated in Figure 3, a narrow operating band around λ_{opt} ensures high thermal efficiency (η_{th}) while minimizing pollutant formation. Larger deviations or broader λ distributions result in reduced combustion quality, incomplete burnout, and unnecessary environmental and efficiency penalties. [12]

Combustion hygiene is therefore a continuous control and monitoring task. It relies on precise regulation of air and fuel flows, consistent burner operation, proper furnace aerodynamics, and rapid corrective actions to compensate for disturbances. By keeping both spatial variations and temporal fluctuations in λ small, the combustion process achieves stable flame conditions,

efficient heat release, and low emissions maximizing the benefits of advanced combustion strategies such as air staging.

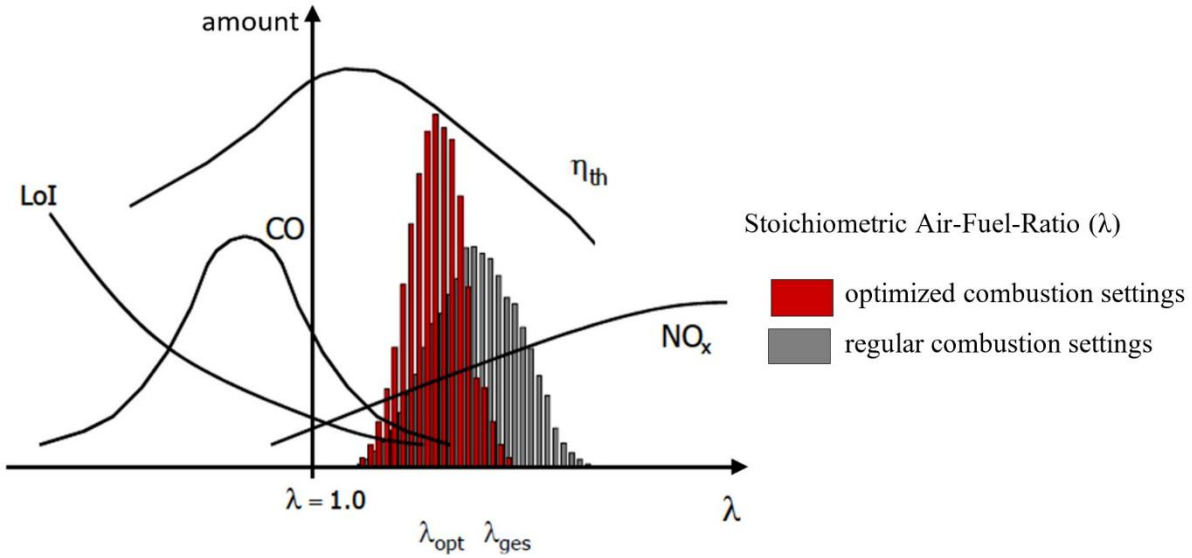


Figure 3: Qualitative plot of the effects of various degrees of the air equivalence ratio λ during combustion.

Maintaining combustion hygiene in large-scale pulverized-coal boilers relies heavily on a clear understanding of how both air and fuel are distributed across individual burners and staging ports. Knowledge of local airflow rates to each burner, as well as the corresponding fuel mass flow, is essential for sustaining the desired stoichiometric conditions throughout the furnace. Having accurate, burner-level information on air and fuel distribution enables operators to identify and correct maldistribution before it degrades combustion quality. [13] Accurate knowledge of air and fuel distribution is therefore a key prerequisite for disciplined combustion hygiene, enabling improved fuel utilization, reduced pollutant emissions, and enhanced operational reliability in coal-fired power plants. [11]

3. Advanced Combustion Monitoring Solutions

The previous section highlighted that precise knowledge of air and fuel distribution to each burner is essential for maintaining optimal λ values and stable combustion hygiene. In practice, this information is often incomplete or only available in aggregate, leaving operators unable to fully balance combustion or quickly react to process fluctuations. The EUcoalflow and EUsoft Air systems close this measurement gap by providing reliable, burner-level data on both fuel mass flow and airflow. With this detailed insight, operators can actively control local air-fuel ratios, minimize deviations from the optimal λ, and ensure that every burner operates in

harmony with improving efficiency, reducing emissions, and enhancing overall boiler performance.

3.1. EUcoalflow Mobile System

Continuous coal mass-flow sensing with the EUcoalflow mobile system applies a non-intrusive microwave-based measurement to resolve the distribution of pulverized fuel in coal-fired boiler



Figure 4 - left: EUcoalflow mobile system components, including mass flow sensors, connector boxes, control unit and laptop. **right:** System lay out as installed at coal mills.

feed lines, as displayed in Figure 4. Figure 5 shows the system's portable microwave transceivers mounted on each coal pipe. These devices emit electromagnetic waves that interact with the flowing coal-air mixture, and the resulting attenuation and phase shift of the waves are sensitive to both the mass flow and velocity within the pipe. [14]

On-site scaling procedures establish the linear relationship between microwave signal characteristics and actual coal mass flow rates under steady-state operating conditions at various load levels. The scaling process utilizes the total mill flow rate measured by gravimetric feeders as the reference standard, achieving measurement accuracy typically within 4% deviation compared to conventional weighing methods. [15] Scaling parameters account for variations in coal properties including particle size distribution, moisture content, ash composition, and coal



Figure 5: EUcoalflow system installed at the various fingers of a coal mill.

type, ensuring measurement reliability across different fuel characteristics. Unlike permanent instrumentation, the mobile and non-intrusive nature of the EUcoalflow system eliminates the risks associated with probe erosion, thermal degradation, or flow disturbance in high-temperature, particulate-laden environments. [16] The absence of durable fixed devices reduces maintenance burdens and operational risk. The resulting dataset constitutes a robust foundation for diagnostics, control calibration, and performance tracking, supporting optimized fuel distribution and underpinning advanced combustion strategies in large-scale pulverized-fuel boilers. [5]

3.2. EUsoft Air System

The EUsoft Air system delivers continuous, burner-level airflow measurements without the need to install any new hardware inside the furnace. Instead of relying on additional instrumentation, the platform ingests the existing signals available in a plant's distributed control system, fan speeds, damper positions, as well as duct and header pressures, and feeds them into a validated network model that faithfully represents the boiler's primary, secondary, and over-fire air pathways, as laid out in Figure 6. By solving this model continuously, the software calculates the mass-flow rate entering every air inlet and then further resolves those totals down to each individual burner port and staging nozzle. The internal solvers update their estimates in real time, which allows the virtual sensor to track rapid transients such as load ramps, damper drift, or pressure fluctuations with high fidelity. [17]

Because EUsoft Air relies exclusively on data already present in the DCS, the approach is entirely non-intrusive: operators avoid the capital cost and downtime normally associated with installing field flow meters or pitot probes, yet they still gain full spatial resolution across the furnace. This is especially valuable in plants with windboxes, where it is not possible to directly measure airflow to individual burners due to the internal geometry and access limitations. At any moment the control room can see the distribution of primary, secondary, and over-fire air delivered to every burner and elevation, rather than inferring it from aggregate header measurements. The system's digital nature also lends it to a remarkable adaptability. Whenever plant conditions change, the model can easily be adapted to the new situation, so that the calculated flows continue to match the actual physical behavior of the air circuits. [18]

Integration into plant operations is straightforward. EUsoft Air streams its live airflow data back into the DCS, where those values can be combined with coal-flow inputs to drive closed-loop combustion control or to alert operators when a burner deviates from its target air-fuel ratio. In

this way, the software not only enhances situational awareness but also provides a practical foundation for process optimization.

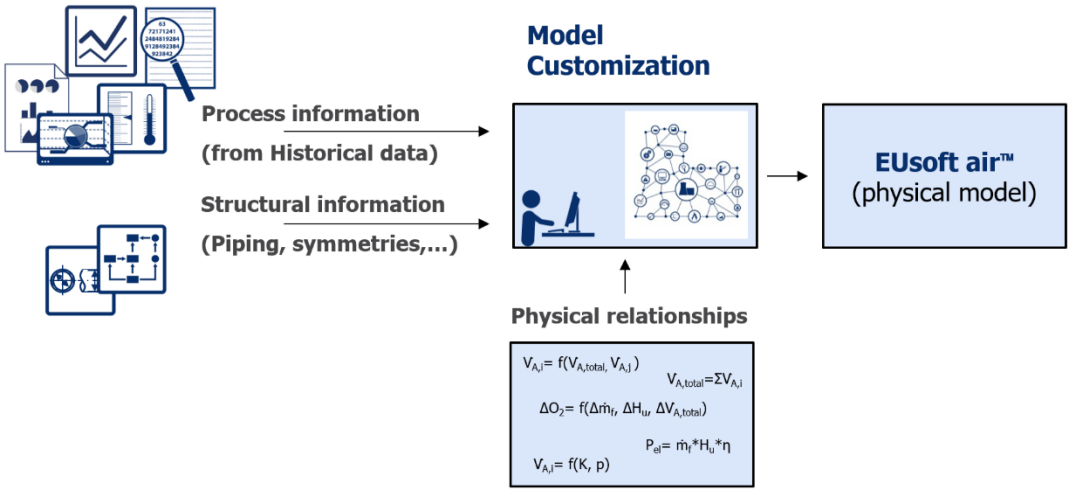


Figure 6: EUsoft Air model building principle.

4. Lambda Mapping

Lambda mapping is the real-time, burner-level determination of the air-fuel equivalence ratio across all combustion stages in a coal boiler. Building on the stoichiometric concepts introduced in Chapter 2 and on the sensor infrastructure described in Chapter 3, the method translates continuous airflow data and periodic coal-flow snapshots into a live, furnace portrait of local stoichiometry. This approach operates on two complementary levels: local λ at each individual burner and cumulative λ for each burner elevation, creating a hierarchical framework that replaces long-standing assumptions about uniform distribution with measured reality.

4.1. The Measurement Gap in Conventional Coal-Fired Power Plants

In most coal-fired power plants, air and coal flows are predominantly measured as aggregate values. [19] Coal input is usually recorded per mill, using belt weighers or feeders, with the underlying assumption that, after leaving the classifier, the fuel is distributed uniformly to all downstream pipes and burners. For combustion air, measurement points are typically only available for larger air flows, such as at the wind box, main duct, or fan outlet. Direct, continuous measurement of airflow at each individual burner or air path is rare. [5]

The actual air distribution is usually inferred indirectly from damper positions and several overall airflow measurements. This is based on the assumption that a given damper opening corresponds to a specific airflow, and that adjusting one damper does not affect flows through the others. In real low-pressure air systems, however, any change in flow resistance at one point

alters the pressure distribution, thereby influencing airflows at all other openings. [17] The relationship between damper position and actual mass flow is nonlinear and is further impacted by factors such as pressure losses, temperature, fouling, and aging. [20]

As a result, precise burner-level air distribution remains unmeasured and is subject to considerable uncertainty with conventional measurement techniques. [21] Advanced analytical methods or virtual sensors, which combine existing aggregate measurements with physical modelling, are required to achieve accurate, spatially resolved airflow determination for optimized combustion control. [17]

4.2. The EUsoft Air and EUcoalflow Solution

This is where the EUsoft Air and EUcoalflow systems come into play. EUsoft Air, as described in Section 3.2, is a virtual sensor that calculates the mass flow for each opening through which air enters the boiler. This model-based approach provides real-time, burner-resolved airflow data without requiring additional intrusive instrumentation.

For coal flow measurement, the EUcoalflow system, as presented in Section 3.1 operates on a different principle suited to the stable nature of fuel distribution patterns. A mill is measured, and the distribution to the individual coal pipes from that mill, essentially per burner, is determined for various load conditions. The distribution is typically not equal in practice, as shown in Figure 7, where the mass flow to each burner of a mill is displayed for various boiler loads, measured at ISKEN with the EUcoalflow mobile system, before optimization.

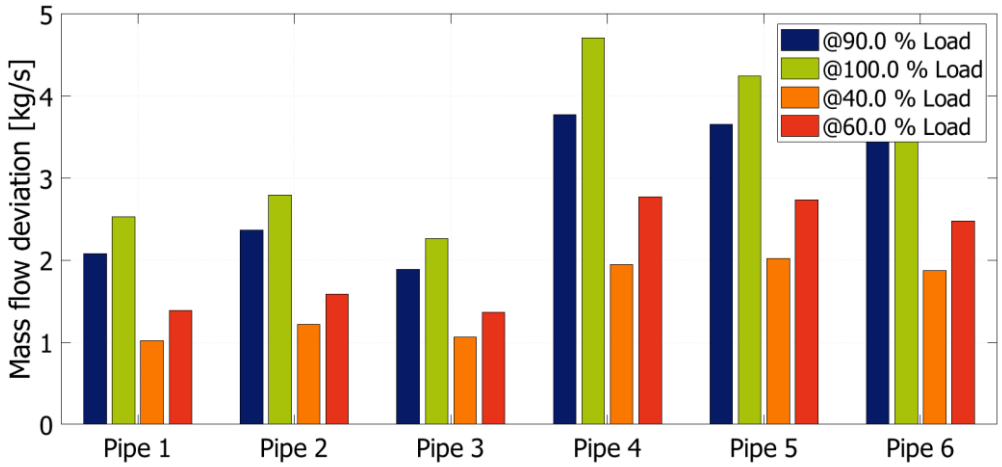


Figure 7: Mass flow to each burner of a mill for various boiler loads, before optimization.

This distribution pattern can be recorded for different operating conditions and stored in the DCS. Although EUcoalflow is a mobile system, its measured distribution for each coal pipe can be transmitted live into the plant's DCS via a standard interface. This embeds the data in the

existing control architecture without any labor-intensive file transfers or complex system modifications. The pipe-to-pipe balance ratio remains relatively constant over time, based on previous assessment of ISKEN. [12] To obtain live data for current operation, the stored ratio is simply multiplied by the respective mass flow that the feeder measures, yielding the coal mass flow per burner. This measure should be updated on a regular basis or when specific changes occur in the system.

4.3. Hierarchical Lambda Calculation

With the approach outlined in the previous section, local lambda can be calculated directly for each burner with the combined data of the EUcoalflow and the EUsoft Air. Once local lambda per burner is available, the integral lambda can be calculated, which is formed from the cumulative lambda of all previous measurement levels plus the current investigated level. This way, the calculation can be accumulated over the entire boiler, through all over-fire air levels, up to the boiler exit, and can be visualized graphically. A conceptual scheme of the approach is displayed in Figure 8. The following equations are exemplary for a boiler with *k* burners per elevation and *l* elevations in total.

Local lambda for burner *i* on elevation *j*:
$$\lambda_{i,j} = \frac{\dot{m}_{air,i,j}}{\dot{m}_{air,stoich,i,j}} \quad (2)$$

Cumulative lambda on elevation *j*:
$$\lambda_{cum,\,j} = \frac{\sum_{s=1}^{j}\sum_{i=1}^{k}\dot{m}_{air,i,j}}{\sum_{s=1}^{j}\sum_{i=1}^{k}\dot{m}_{air,stoich,i,j}} \quad (3)$$

Cumulative lambda for the whole boiler:
$$\lambda_{boiler} = \frac{\sum_{j=1}^{l}\sum_{i=1}^{k}\dot{m}_{air,i,j}}{\sum_{j=1}^{l}\sum_{i=1}^{k}\dot{m}_{air,stoich,i,j}} \quad (4)$$

The hierarchical approach enables both immediate local corrections and strategic plant-wide optimization. Local lambda values provide the granular control needed for individual burner adjustments, while integral lambda values at each elevation support coordinated combustion strategies across the furnace height, as derived in Section 2.3.

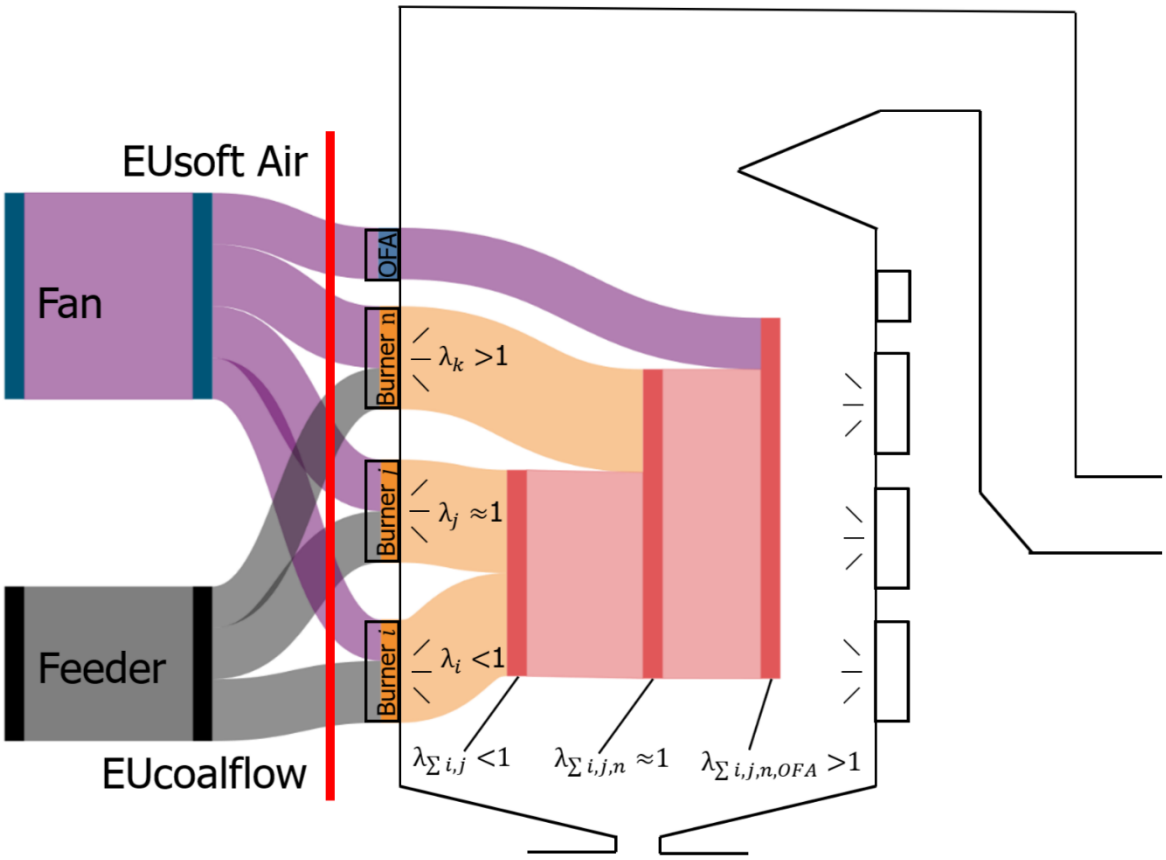


Figure 8: Lambda mapping concept, enabled by combination of EUcoalflow and Eusoft Air measurement.

5. Conclusion

Lambda mapping at ISKEN Sugözü integrates EUcoalflow and EUsoft Air to replace uniform distribution assumptions with direct, burner-level measurements of coal and air flows. Situational microwave sensing of coal mass flow in combination with real-time virtual airflow modeling yield local stoichiometric equivalence ratios at each burner. Hierarchical lambda calculations accumulate these values through all over fire air levels to the boiler exit, enabling spatially resolved stoichiometry visualization. This methodology addresses measurement gaps in conventional plants where only aggregate flows are available and provides the data needed for precise air-fuel ratio control. By revealing actual sub-stoichiometric and fuel-lean zones, lambda mapping supports targeted adjustments to air staging, reduces NO_x formation, ensures complete fuel burnout, and enhances combustion hygiene. The nonintrusive installation and seamless DCS integration facilitate retrofitting without major outages, laying the groundwork for advanced, data-driven combustion control in large-scale coal-fired boilers.

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