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DECARBONIZING ASPHALT MIXING PLANTS WITH ELECTRIFICATION AND ENERGY STORAGE

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Summary

Asphalt production requires high-temperature drying and heating of mineral aggregate and reclaimed asphalt pavement, conventionally gas-fired and thus a significant CO_2 source. Its 1000–2000 annual full-load hours coincide well with periods of low-cost PV electricity. This study assesses direct electrification with resistance heaters, combined with high-temperature thermal energy storage (TES), warm material storage (WS) or battery storage (BESS) and a gas or hydrogen backup, for a real 20 MW_{th} German batch plant. Day-ahead electricity price projections up to 2044 are derived from an energy-system model via a neural-network price model, complemented by natural gas and hydrogen price projections including grid fees. Driven by these prices, minute-resolved annual simulations with a price-driven rule-based dispatch strategy determine the operation of heaters, storage and backup burner. The results feed a 20-year discounted cash-flow analysis in which storage size and control thresholds are optimized.

As a measure preceding electrification, reducing feedstock moisture and drying air flow lowers the thermal demand by 10–25 % and thus the required storage capacity. Even without storage, dynamic electrification reaches electric heat shares of 30–40 % at costs comparable to the gas reference; with suitable storage, electric heat shares of 50–60 % and CO_2 reductions well above 40 % are achieved, with WS being the most cost-competitive option and TES reaching comparable economics while being easier to integrate. With a hydrogen backup and renewable electricity, electrified hybrids exceed 90 % electric heat share and thus enable virtually full decarbonization, at far lower cost than a hydrogen-only supply, whose lifetime cost roughly doubles that of the gas reference. Since CAPEX dominates at such low full-load hours, public investment support is the key lever for the preferred combination of resistance heaters, TES or WS and a fuel-fired backup.

Keywords: asphalt plants, industrial process heat, electrification, thermal energy storage, warm material storage, battery, hydrogen, techno-economics, decarbonization

Field of application for the findings: Industrial high-temperature drying/heating, asphalt production.

Addressed audience: Researchers and practitioners in renewable process heat, thermal storage, industrial electrification and energy systems; equipment suppliers, plant operators and policy makers.

1. Introduction

Asphalt production requires high-temperature drying and heating of mineral aggregates and reclaimed asphalt pavement (RAP/RC) in rotary drums, typically supplied by large natural gas, oil or even coal burners and thus associated with high CO_2 emissions. In Germany, asphalt demand is strongly seasonal and concentrated in day-time hours on working days, with only about 1000–2000 annual full-load hours. This profile matches well with the availability of low-cost electricity from solar PV. At the same time, the energy price landscape is changing: natural gas becomes considerably more expensive as CO_2 costs rise, electricity prices show increasingly large intra-day spreads with frequent low-price hours, and hydrogen is expected to remain comparatively costly over the next two decades.

This work investigates how direct electrification combined with flexibilization through storage can exploit these evolving price structures to decarbonize asphalt production cost-effectively. For a typical German plant with 20 MW nominal thermal power, we quantify the techno-economic performance of several hybrid electrification concepts, using electric resistance heaters together with high-temperature thermal energy storage (TES, see Fig.1), battery energy storage (BESS) or warm material storage (WS), and a fuel-fired backup (natural gas or hydrogen). The concepts are assessed with minute-resolved annual simulations and dynamic, price-based control over a 20-year horizon, and are compared against combustion-only reference systems under a range of economic scenarios covering energy prices, CAPEX funding rates and backup fuel type. In addition, we consider moderate process-side efficiency measures, in particular reduction of feedstock moisture and drying air flow, as a complementary lever that lowers the thermal demand and thereby the required energy costs.

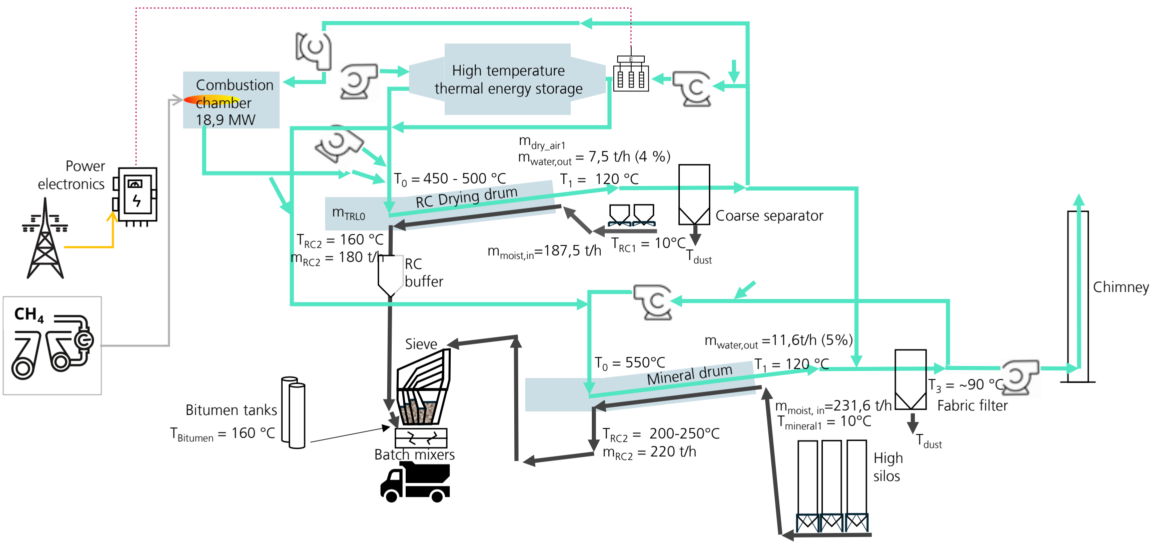

Fig. 1: Schematic layout of an electrified asphalt plant with resistance heaters and thermal energy storage

2. Methodology

The assessment starts from a real, gas-fired reference plant and evaluates a set of electrified concepts against it under consistent boundary conditions and long-term energy price scenarios. All concepts are required to serve the same fixed annual asphalt production profile and share identical grid connection limits, so that differences in cost and emissions arise solely from the heat supply and storage configuration. In the following, we first describe the reference plant and boundary conditions, then the electrification and storage concepts, the energy price projections, the minute-resolved dynamic simulation and control, and finally the techno-economic assessment.

2.1 Reference plant and boundary conditions

The reference system is a real, gas-fired 20 MW_{th} batch plant defined together with the equipment manufacturer Benninghoven, processing both virgin aggregate and reclaimed asphalt pavement (RAP) in two separate rotary drums. Its key parameters are summarized in Table 1. A real production profile of this plant was made available and serves as the fixed, weather-independent annual demand that every concept must satisfy at all times, ensuring comparability across variants.

Tab. 1: Key parameters of the gas-fired reference plant and the electrified variants.

Parameter	Value
Nominal thermal capacity	20 MW_{th}
Share of reclaimed asphalt (RAP)	~30 %
Moisture content (aggregate / RAP)	~5 % / ~4 %
Dryer outlet temperature, aggregate	250–300 °C
Dryer outlet temperature, RAP	130–180 °C
Bitumen temperature	160 °C
Dryer gas outlet temperature	100 °C
Gas / hydrogen burner efficiency	95 %
Electric heater efficiency	100 %
Electric grid connection	20 MW

The production data confirm the discontinuous nature of asphalt manufacturing, which is concentrated on working days in the dry season and largely absent on weekends and during cold or rainy periods. As only about ten months of operational data could be extracted, representative seasonal weekly profiles were duplicated and, where sensors were faulty, filtered or virtually recalibrated in agreement with the manufacturer to obtain a complete annual data set. For all concepts, the electricity grid connection is limited to 20 MW, and electricity is purchased cost-optimized against day-ahead prices, without cross-market optimization (e.g. intraday or ancillary services).

2.2 Electrification and storage concepts

Starting from the combustion-only reference, we consider electrified concepts that replace or supplement the burners with electric resistance heaters, optionally combined with a storage component and a fuel-fired backup (natural gas or hydrogen).

Fig. 2: Electrification and storage concepts, each with a gas or hydrogen backup: electric heaters with battery storage (BESS, left), with high-temperature thermal energy storage (TES, center) and with warm material storage (WS, right).

Resistance heating is chosen over dielectric alternatives (micro-/radio-wave, plasma) because of its high efficiency (~98 %), lower specific cost (~110 €/kW including control) and its ability to supply both the ~550 °C hot air for direct drum integration and the ~800 °C level required for storage charging: the specific investment of dielectric heating rises with frequency, while its efficiency stays below that of resistance heating (Fraunhofer ISI, 2024). In addition, dielectric heating of the material itself may disintegrate mineral grains, an effect also discussed for mining applications (Ahmadihosseini et al., 2025), and thereby alter the grading and violate quality criteria. A shared advantage of flame-free electric heating is the gentler treatment of the RAP, which reduces the self-ignition risk and can improve product quality. All concepts must satisfy the same fixed annual production profile and share identical 20 MW grid limits, so that differences arise solely from the heat supply configuration.

Three storage options are investigated (Fig.2). The high-temperature thermal energy storage (TES) is a sensible packed-bed store using air as heat transfer fluid and a composite of about 85 % recycled steel-slag granulate as storage material, operated up to ~800 °C with a usable state-of-charge range of 10–90 %; effective storage costs are on the order of 36–60 €/kWh_{th} (solarthermalworld.org, 2024). The warm material storage (WS) instead buffers already dried and heated aggregate and RAP in insulated silos, which is cheaper per unit capacity but more process-specific. The battery energy storage (BESS) is realized in lithium iron phosphate (LFP) technology, selected for its low cost, cycle stability, safety, temperature robustness and broad availability; charging and discharging are limited to 20 MW within a 10–90 % operating window. For all variants, the fuel-fired backup can be operated on natural gas or, for full decarbonization, on hydrogen using a fuel-flexible burner; such burners are commercially available (BENNINGHOVEN GmbH & Co. KG, 2023) and hydrogen firing has already been demonstrated in Norwegian asphalt production (Veidekke ASA, 2022).

2.3 Energy price projections

All concepts are evaluated against consistent long-term projections of day-ahead electricity, natural gas and hydrogen prices up to 2044. The electricity prices are derived through a model chain: hourly generation, load, gas and CO_2 price trajectories from the national energy-system model REMod (Fraunhofer ISE, 2026; Thelen et al., 2024) feed an artificial neural network that reproduces day-ahead spot prices. The network is trained on historical data (2020–2023) and validated against the withheld year 2024 before being applied to the future REMod scenarios; here we use the *technology-open* scenario. Price data for the simulations was generated for the years 2024, 2028, 2032, 2036, 2040 and 2044, with differing underlying meteorological data.

For the end-customer perspective, grid fees, taxes and levies are added on top of the wholesale prices for each energy carrier, based on the projections of Agora Energiewende (2025). Only flat grid fees are considered: for industrial electricity consumers these amount to about 5–6 €ct/kWh (slowly declining network charges plus levies), while the natural gas grid fee is low but rises from about 1 to 2 €ct/kWh towards 2044, reflecting the shrinking gas demand and network utilization. One-time grid connection charges and construction cost subsidies are not considered. A more complex, variable fee structure (e.g. separate energy- and demand-based components) is not modelled here; such fees could in turn be mitigated through flexibilization with larger thermal or electrical storage.

Three trends dominate the resulting projections and drive the results in Section 3. First, the effective natural gas price rises substantially from about 6 to 14 €ct/kWh as CO_2 costs increase, narrowing the gap to the average electricity price of roughly 14 €ct/kWh. Second, the spread between low- and high-price electricity hours widens markedly, since bridging low-renewable-generation periods increasingly relies on expensive fuels. Third, hydrogen is expected to fall from about 22 to 18 €ct/kWh with the assumed market ramp-up towards 2040, but remains the most expensive carrier throughout the horizon.

For hydrogen, two supply routes are distinguished. Grid-based supply via the emerging hydrogen core network is expected from about 2030 onwards, with prices declining markedly towards 2040; where a pipeline connection is unavailable, costlier truck delivery would be required. As an alternative, on-site generation with a 20 MW PEM electrolyzer and hydrogen storage was assessed, operating the electrolyzer only in hours with sufficiently low electricity prices. The resulting levelized cost of hydrogen is competitive with the pipeline supply, with a cost optimum at electricity price thresholds around 11–12 €ct/kWh and 3300–3800 full-load hours; coupling to a dedicated 20 MWp PV plant lowers it further. On-site generation can therefore be attractive at sites with sufficient area and investment capacity, although these results were not feed back into the hydrogen prices used in the subsequent simulations, which rely on the pipeline projection.

2.4 Dynamic simulation and control

The asphalt production process and its energy supply are modelled in the Fraunhofer ISE in-house software ColSim (Rohani et al., 2025), using a time step of 1 min. Thanks to its performant C++ implementation, high-resolution annual simulations run on a single CPU within minutes, so that several thousand parameter variations could be evaluated through parallelization. The support years 2024, 2028, 2032, 2036, 2040 and 2044 are simulated explicitly, and intermediate years are interpolated. On the demand side, the model represents the material flows (aggregate, RAP, moisture and air), the two drying drums, material buffers and the mixing process; on the supply side, it covers the gas, hydrogen and electric heaters, the storage components (TES, BESS or WS) and the auxiliaries.

The simulation is driven by input time series for the fixed production profile (aggregate and RAP mass flows, RAP share and required drum outlet temperatures) and for the day-ahead electricity, gas and hydrogen prices of the respective scenario. It returns output time series of the quantities needed for the subsequent evaluation, in

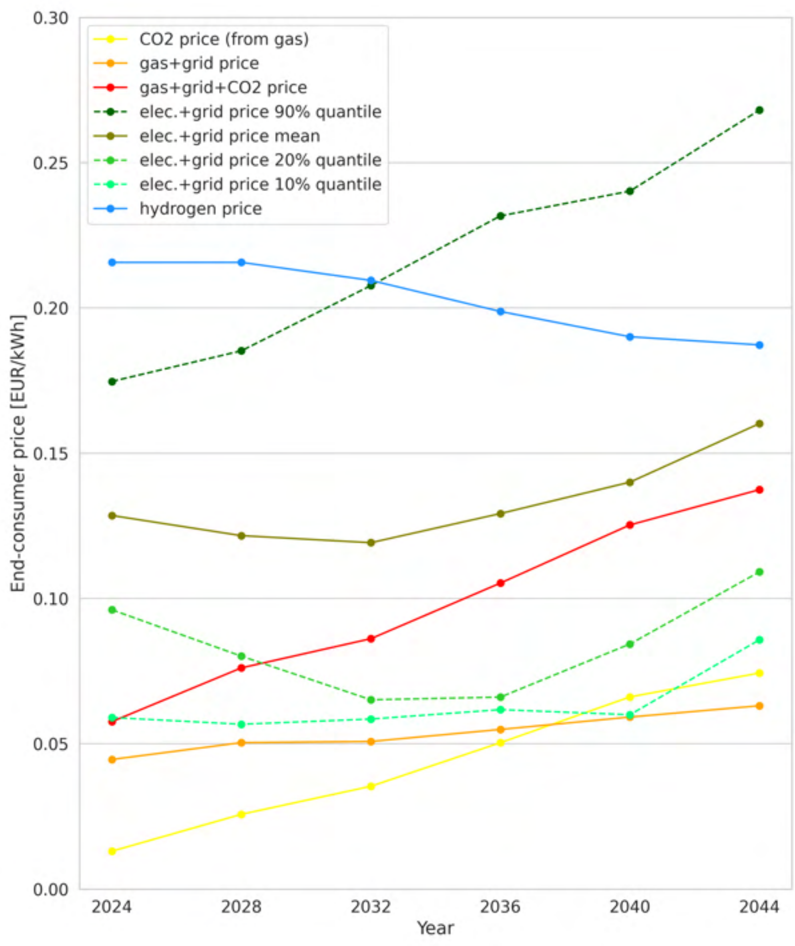

Fig. 3: Projected average annual end-customer prices including grid fees for electricity, natural gas and hydrogen for industrial consumers, 2024–2044.

particular the electric, gas and hydrogen heater powers, the grid power, the storage charging/discharging power and state of charge, and the resulting energy costs and CO_2 emissions. These minute-resolved outputs are aggregated to annual and, via the support years, discounted lifetime values for the techno-economic assessment.

A rule-based control strategy dispatches the heat supply based on the day-ahead electricity price, the current storage SOC and the ongoing production; its behaviour is illustrated for two exemplary weeks in Fig.4, where markers highlight the characteristic situations discussed below. Two limits govern the decision (marker 3): the effective price of the backup fuel (natural gas or, alternatively, hydrogen) forms a constant upper limit (`elec_price_max`), while a dynamic threshold (`elec_price_threshold`) is derived from a quantile of the day-ahead price over a 36 h horizon and modulated by a SOC-dependent factor (`mtsi_fraction`). Whenever the electricity price exceeds the upper limit, heat is provided by the backup burner instead of the grid; when it falls below both limits outside production hours, the electric heater charges the storage from the grid (marker 4). As the `mtsi_fraction` runs roughly counter to the SOC, it shifts the admissible price quantile and thereby triggers the switches between discharging and charging (marker 6), so that the storage is preferentially charged in low-price hours and discharged when prices rise.

The fixed production load profile must be met at all times, which constrains the dispatch and, together with the storage size, determines the achievable electric heat share (*electric fraction – EF*). Markers 1 and 5 show the resulting fallback: with the storage at its lower SOC limit and the electricity price above the threshold, the aggregate and RAP backup burners cover the demand — in the situation of marker 1 at similar thermal power for both drums, although the RAP mass flow exceeds the aggregate mass flow, since RAP requires a lower outlet temperature and contains less moisture. The usable SOC window of 10–90 % is reached repeatedly (marker 2), which caps the amount of energy that can be shifted between hours and thus links the storage size directly to the achievable electric heat share, as analyzed in Section 3.

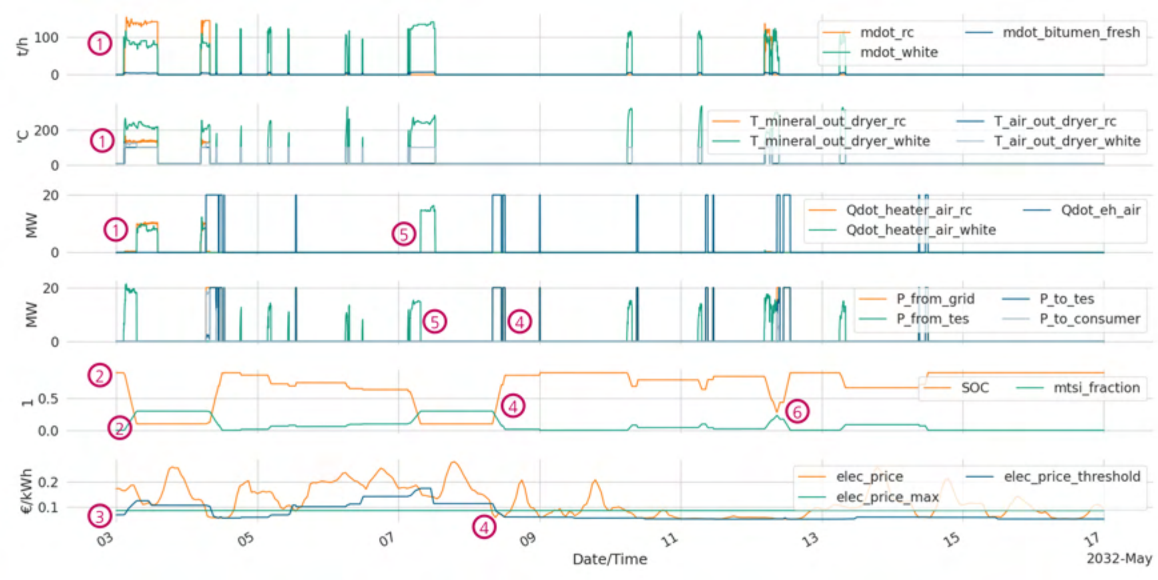

Fig. 4: Exemplary two weeks of plant operation (TES concept with 100 MWh, base electricity price scenario with the effective gas price as upper limit, May 2032). From top: aggregate, RAP and bitumen mass flows; material and air outlet temperatures of both drums; thermal power of the electric heater and of the aggregate/RAP backup burners; grid, TES and process power; storage SOC and threshold factor (`mtsi_fraction`); electricity price with dynamic threshold and upper limit. Markers 1–6 are discussed in the text.

2.5 Techno-economic assessment

Each configuration is evaluated by a discounted cash-flow analysis over a 20-year lifetime, using a weighted average cost of capital and discount rate of 5 %. The investment (CAPEX) comprises the electric heaters, the storage component and the auxiliaries, together with markups for balance of plant, engineering, procurement and commissioning, and project development; for the battery variant, a replacement after 15 years is included. A CAPEX funding rate of 50 % is assumed in the base case, reflecting the importance of public investment support for these low-utilization plants. The annual operating expenditure (OPEX) is set to 1 % of CAPEX and complemented by the energy costs for electricity and backup fuel, which follow directly from the simulated dispatch and the price projections.

For every concept, the storage size and the key control parameters (mainly the price thresholds for charging and dispatch) are varied to minimize the discounted lifetime cost for the given production. From each optimized configuration we derive the discounted lifetime cost, the cumulative CO_2 emissions and the electric heat share, i.e. the fraction of process heat supplied directly or via storage by electricity. These three indicators form the basis for the cross-concept comparison in Section 3.

CO_2 emissions are evaluated consistently with the dispatch: the fuel side from the simulated gas consumption with an emission factor of 0.201 $kg\,kWh^{-1}$ (LHV), hydrogen as carbon-neutral, and the electricity side from the minute-resolved grid demand multiplied by hourly emission factors of the German power mix from the same REMod scenario. Note that the CO_2 costs of grid electricity are already contained in the day-ahead price, whereas the fuel-side CO_2 price is added explicitly. Supply with renewable electricity sets the electricity-side emissions to zero, so that a hybrid concept with hydrogen backup reaches full decarbonization.

3. Results and Discussion

We first quantify the process-side efficiency measures, then the hybrid electrification concepts with gas and hydrogen backup, followed by the specific role of battery storage.

3.1 *Process-side efficiency measures*

Before electrifying the heat supply, a systematic heat demand analysis of the average process was used to quantify how far the thermal demand itself can be reduced (see Fig.5). In the reference process, the largest energy shares are the heating of the mineral aggregate and – almost equally large – the evaporation of the moisture contained in aggregate and RAP, so that the feedstock moisture content strongly governs the energy demand. Reducing the moisture content by 2–3 %-pts, e.g. through mechanical dewatering or better-covered storage, lowers the thermal demand by roughly 20–25 %, with a corresponding cut in gas consumption and CO_2 emissions.

A second lever is the reduction of the drying air flow, which becomes feasible especially with electric heating via a recirculated bypass, where in the ideal case the drum contains essentially steam rather than air. This yields a further reduction of about 15 %, and combining both measures gives a theoretical demand-reduction potential on the order of 35 %, although for realistic parameter ranges a reduction of about 10–25 % is to be expected. Because these measures also shrink the storage capacity required to reach a given electric heat share, they act as a direct complement to the electrification concepts.

The flue gas of the established process leaves the drums at about 100 °C and carries a waste-heat potential of more than 60 % of the input energy when cooled down to 30 °C, largely through condensation of the evaporated and combustion-generated water. Directly reusing this waste heat to preheat the drying air offers only about 5 % savings, whereas integrating heat pumps together with an additional tunnel dryer or drum could reduce the combustion energy demand by up to 60 %. Reducing the moisture content, however, also lowers the recoverable waste-heat potential by about 60 %, so the two routes partly compete and should be weighed against their respective CAPEX.

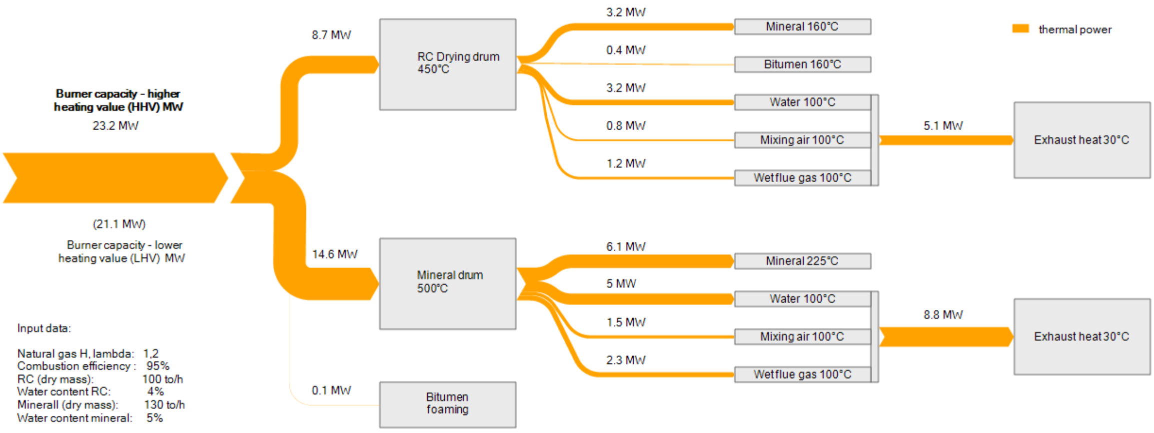

Fig. 5: Exemplary instantaneous energy flows of the asphalt production process (status quo), illustrating the shares of aggregate heating, moisture evaporation and the recoverable waste heat.

3.2 *Hybrid concepts with gas backup*

We first benchmark the electrified concepts against the gas-fired reference, using the effective natural gas price as the upper limit for electricity purchase (Fig.6). Even without any storage, direct electrification with resistance heaters and dynamic operation against day-ahead prices reaches electric heat shares of roughly 30–40 %, at discounted lifetime costs comparable to the gas-only reference. This confirms that a substantial part of the drying and heating demand can be covered during low-price hours, before any storage is added.

Adding a storage component raises the electric heat share and lowers CO_2 emissions further, at the expense of additional investment. Already a small 40 MWh store lifts the electric heat share to more than 50 % and cuts the annual CO_2 emissions by about one half relative to the reference, largely independent of the storage technology. With larger storage, the electric heat share may rises to 60–80 %. The warm material storage is the most cost-competitive option owing to its low CAPEX, with a techno-economic optimum around 43 MWh and an electric heat share above 50 %. The high-temperature TES achieves comparable overall economics and, as a clearly separated component, is easier to integrate into existing layouts. The battery variant remains more expensive, however: its investment is significantly higher than the TES case and requires a replacement after 15 years, so that its discounted lifetime cost lies clearly above the reference, whereas the TES concept stays within a few percent of it.

Overall, the hybrid concepts with gas backup keep the levelized cost of heat close to or below the gas-only reference while cutting CO_2 emissions by well over 40 %, so that electrification is already competitive under the base price scenario.

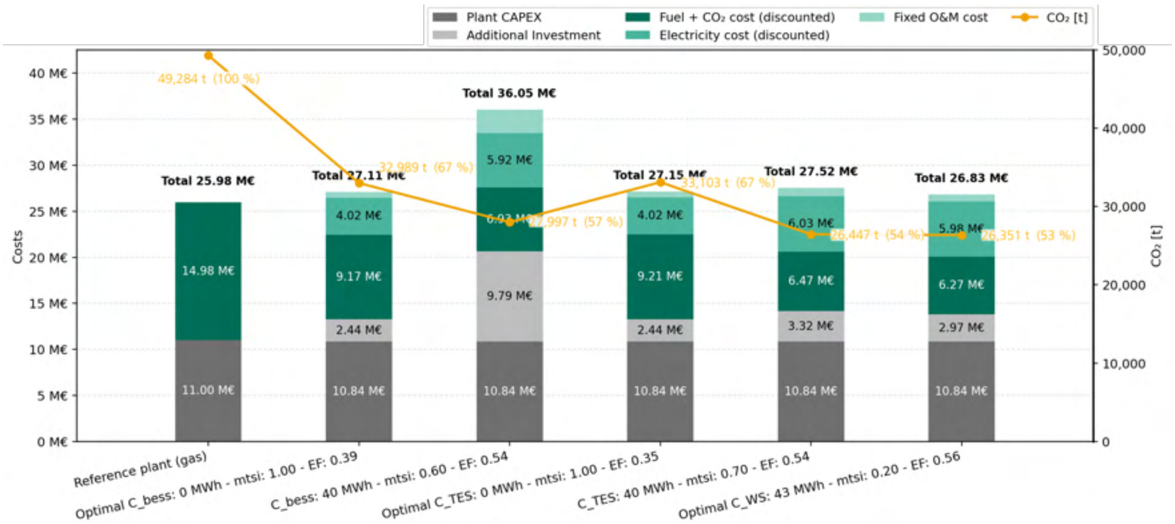

Fig. 6: Comparison of the concepts in the base scenario with natural gas as backup fuel and price limit, at a CAPEX funding rate of 50 %: discounted 20-year cost, electric heat share EF and cumulative 20-year CO_2 emissions of the gas-only reference plant and of the cost-optimal BESS, TES and warm material storage hybrids. For BESS and TES, the cost optimum contains no storage, so an additional variant with a fixed storage capacity is shown for illustration.

3.3 Hybrid concepts with hydrogen backup

For sites aiming at full decarbonization of the fuel side, the natural gas backup is replaced by a hydrogen burner, and the hydrogen price serves as the upper limit for electricity purchase (Fig.7). The benchmark is now a hydrogen-only reference, whose discounted lifetime cost is far higher than that of the gas-fired plant, reflecting the persistently high hydrogen price over the whole horizon. Against this reference, all three electrified hybrids (BESS, TES and WS) become even more attractive than in the gas case and are clearly cheaper than supplying the plant with hydrogen alone.

Because hydrogen is the most expensive carrier, the optimization shifts as much heat as possible to electricity, so the electric heat share exceeds 90 % for all three storage concepts. For the BESS variant, the optimum contains no dedicated storage at all, i.e. pure direct electrification already reaches an electric heat share above 90 %, whereas the thermal storage concepts favor comparatively large capacities of about 80 MWh (TES) and 65 MWh (WS). Hydrogen is then only fired in a small number of high-price hours, which is precisely what keeps these hybrids far below the hydrogen-only reference in cost.

Since the hydrogen backup itself is carbon-neutral, the hydrogen-only reference reaches zero direct emissions, whereas the residual emissions of the hybrids in Fig. 7 stem solely from grid electricity and amount to roughly 30–36 % of the gas-reference emissions. With renewable electricity, these residual emissions vanish as well, so that the hybrids reach full decarbonization at a fraction of the hydrogen-only cost.

3.4 Battery storage

As mentioned previously, the evaluation of the battery storage concept did not consider additional revenue streams from electricity market participation and assumed that the battery is exclusively operated to support the asphalt production process. This reflects the feedback received from asphalt plant operators during the project in 2025, for whom active participation in electricity markets was generally not considered part of the core business. Consequently, the economic assessment of the BESS concept should be regarded as conservative. To

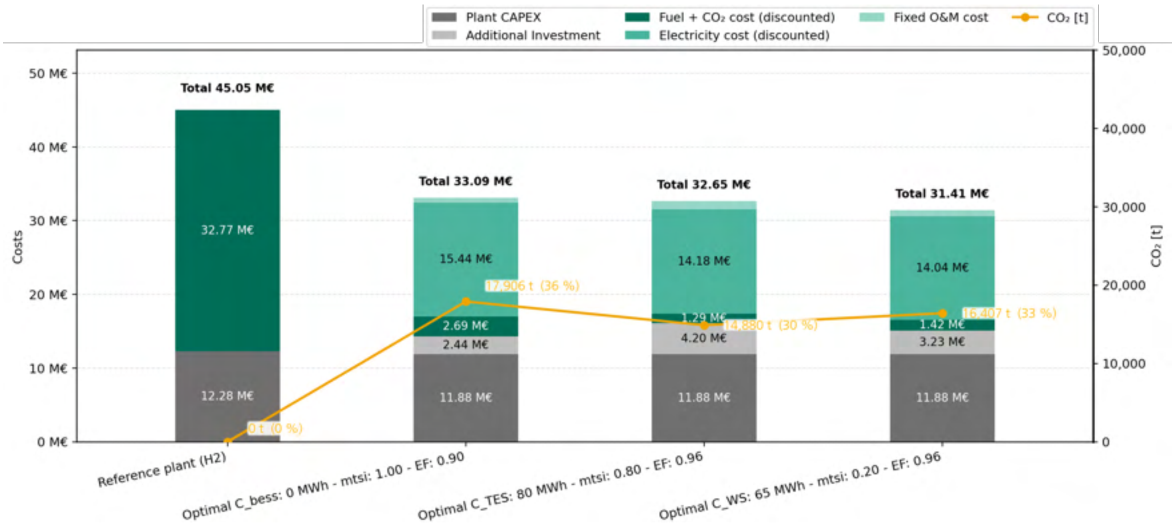

Fig. 7: Comparison of the cost-optimal concepts in the base scenario with hydrogen as backup fuel and price limit, at a CAPEX funding rate of 50 %: discounted 20-year cost, electric heat share EF and cumulative 20-year CO_2 emissions of the hydrogen-only reference plant and of the BESS, TES and warm material storage hybrids; for BESS, the cost optimum contains no storage.

provide an indication of the possible order of magnitude of these omitted revenues, a simplified estimate was performed based on recent German battery market observations. Given the highly seasonal nature of asphalt production, with very limited production typically occurring between November and February, the battery could potentially be made available almost entirely for market participation during these months.

For an illustrative estimation of the potential order of magnitude, revenue levels reported by Battery Charts (RWTH Aachen University, 2026) for the German day-ahead and intraday electricity markets over the preceding 12 months were used as a reference. During the winter period, market revenues of approximately $50\,\text{k€}\,\text{MW}^{-1}\,\text{a}^{-1}$ are assumed. During the remaining months, the revenue potential is assumed to exceed $150\,\text{k€}\,\text{MW}^{-1}\,\text{a}^{-1}$. During the production season, the battery dispatch is optimized to meet the requirements of the asphalt production process. Conservatively, only one third of the battery operating hours is then assumed to remain available for market participation. Based on these assumptions, the average revenue potential is approximately $50\,\text{k€}\,\text{MW}^{-1}\,\text{a}^{-1}$.

For the 20 MW / 40 MWh battery system considered in this study, this corresponds to approximately 1 M€ of additional annual revenue. Using the same economic framework as applied in the techno-economic assessment, including a 20-year project lifetime, a 5 % discount rate, and a full battery replacement after 15 years, the net present value of these additional revenues remains in the order of 9 M€. This value is comparable to the additional lifetime costs that currently penalize the BESS concept relative to the thermal energy storage alternative. It should be emphasized that this estimate is intended solely to illustrate the potential order of magnitude. The actual revenue potential depends on battery degradation, plant-specific operating schedules, future electricity market developments, and the share of battery capacity available for market participation. As these sensitivities were not considered in the present analysis, the economic performance of the BESS concept is likely underestimated.

4. Conclusions

Minute-resolved annual simulations with dynamic, price-based control and techno-economic optimization show that asphalt mixing plants can be deeply decarbonized in a cost-competitive way, by combining moderate process-efficiency measures with direct electrification and suitable storage. The analysis rests on long-term energy price projections in which the effective natural gas price rises strongly with increasing CO_2 costs, while electricity prices exhibit widening intra-day spreads, so that purchasing electricity in low-price hours becomes progressively more attractive than firing gas. Substituting gas entirely with carbon-neutral hydrogen nearly doubles the discounted lifetime cost of the reference plant, confirming that hydrogen remains the most expensive carrier over the whole horizon.

Already without any storage, direct electrification against day-ahead prices reaches electric heat shares of roughly 30–40 % at lifetime costs comparable to the gas-fired reference, i.e. significant electrification and decarbonization are possible even before adding storage. Adding a suitably sized store raises the electric heat share to about 50–60 % and cuts CO_2 emissions by well over 40 %. Warm material storage is the most cost-competitive option owing to its low CAPEX, though it is more process-specific, whereas high-temperature TES offers comparable overall economics with simpler integration as a clearly separated component. The hybrid concept combining electric resistance heaters, TES or warm material storage and a fuel-fired backup boiler is therefore competitive and should be pursued as the preferred solution.

Battery storage plays a more specialized role: dedicated to shifting electricity for process heat only, it is not competitive at current CAPEX. However, a battery can become attractive when it additionally participates in intraday or ancillary-service markets, or when it is limited to the non-thermal plant loads.

Hydrogen, in turn, enables full fuel-side decarbonization and can serve as a backup in an electrified supply, which is sometimes mandated by legal or regulatory boundary conditions; whether this offers economic advantages over a solution without backup remains subject to future work. Because these plants operate at low annual full-load hours (below 2000 h), CAPEX dominates over OPEX and energy costs, so that public investment support is a key lever to accelerate implementation of these decarbonization pathways. Finally, low-cost measures to reduce the feedstock moisture content are advisable, since they lower the thermal demand — and thus operating costs and the required storage capacity — at comparatively little additional CAPEX, and can be complemented by internal waste-heat use or heat pumps.

Outlook

Beyond the German case study, electrification of asphalt production has large potential across Europe for energy-cost reduction, decarbonization and enhanced supply resilience. Other markets differ in their production profiles and electricity price structures, so transferring the approach to further European countries is a natural next step. Future work should also assess non-economic key performance indicators such as the resilience of the energy supply and cost-planning security, which may favor electrified concepts beyond their direct economics. On the modelling side, the simulation environment can be developed into a digital twin that accompanies plant operation: combined with model predictive control, it anticipates prices and upcoming production and thereby supports the operator in dispatching heaters, storage and backup burner to further increase profitability.

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