

# Techno-economic optimization of industrial energy systems using Energy System Design:

## Cost-optimizing decarbonization for pulp and paper mills

SIEMENS energy

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## Authors


**Joshua Brooks, PhD**
**Siemens Energy**
**Orlando, United States**

**Stefan Bruche, PhD**
**Siemens Energy**
**Berlin, Germany**


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# 1 Executive summary

The pulp and paper industry faces unparalleled financial and environmental challenges stemming from forestry practices, greenhouse gas emissions, and waste management techniques. Among these, the energy systems used in pulp and paper production processes have gained significant attention, accounting for up to 30% of operating costs and contributing to substantial greenhouse gas emissions.

Siemens Energy has developed an optimization method for energy system designs that holds the potential to markedly enhance the efficiency, cost-effectiveness, and environmental footprint of powering pulp and paper facilities. This design strategy helps mills minimize costs, curb carbon emissions, boost grid independence, and elevate the overall operational performance and reliability of their energy systems.

This whitepaper discusses efficient energy management technologies and practices within pulp and paper mills while exploring contemporary renewable, conventional, and hybrid electrical and thermal energy solutions for powering mill process systems. Siemens Energy's Energy System Design method is introduced as a holistic approach to identifying energy system designs which meet the technical, financial, and environmental targets of our customers. A case study details the Energy System Design process at work in designing the energy system for a real customer's paper machine expansion project. The study identified energy system designs that reduced cost by up to 22.1% while reducing $CO_2$ emissions by up to 26.8% than the originally planned energy system (i.e. reference system). Multiple energy system designs are discussed with their sensitivity to uncertainty in the study's assumptions and information. Dispatch profiles are included to demonstrate the operational differences and opportunities between a cost-optimized design and the reference system. Finally, a decarbonization roadmap is delivered by identifying cost-optimized energy system designs with progressively lower $CO_2$ emissions. This work considers hourly-matched $CO_2$ emissions accounting to identify energy system designs that show a progressive decrease in $CO_2$ emissions, ultimately leading to the development of a so-called 24/7 carbon-free energy system. This exercise offers customers a practical tool for understanding the cost of decarbonization and what technologies and operating strategies may be required for their energy system.

Energy System Design supports the optimization of energy systems for industrial applications. This powerful tool delivers concepts for turnkey energy system solutions complete with technology selection, sizing, and operation within one integrated optimization procedure. A successful energy transition requires balancing affordability, reliability, and sustainability. Siemens Energy works with our industrial customers to exploit each of these in their current and future energy systems by guiding the selection and configuration of energy conversion and storage assets, identifying utilization opportunities for waste streams, and producing world class energy generation, transmission, and storage technologies.

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# 2 Pulp and paper industry and its energy usage

A The global pulp and paper industry is valued at over 350 billion USD and is expected to grow well into the future with the shift from newsprint and printing and writing material toward packaging board for consumables [1]. Globally, over 400 million metric tons (Mmt) of paper products are produced by over 700 virgin pulp mills and nearly 6,000 paper machines before even considering secondary fiber (recycled) repulping operations [2,3]. To accomplish this, pulp and paper mills consume massive amounts of energy in driving processes and generating steam.

Pulp and paper mills are historically resourceful energy managers, generating as much as 65% of their electrical and steam requirements on-site by recovering and burning process materials (black liquor, solids and other extractives) and other wood byproducts. In addition, mills generally recover waste heat and steam to minimize freshwater consumption and unnecessary auxiliary heating [3, 4]. Even still, the remaining energy requirement must be met by on-site power and steam generation using fossil fuels or through external power and steam purchases. This supplemental power requirement accounts for up to about 15% and 23% of the total operating costs for virgin pulp mills and paper machines, respectively [4, 5]. The U.S. pulp and paper industry consumes billions of dollars on purchased fuels and electricity annually [6]. In addition to the financial cost, supplemental power consumption by US pulp and paper mills contributed to the industry's estimated 31.2 Mmt of $CO_2e$ emissions in 2022 alone [7]. Improving the energy efficiency of both the processes inside pulp and paper mills and the energy systems used for powering these is therefore, an imperative toward reducing overall plant costs and carbon emissions.

There are opportunities available to significantly improve the energy efficiency of many of the core processes within pulp and paper mills. Figure 1 presents the energy consumption of industry-standard technology against both state-of-the-art technology available today and the ultimate thermodynamic minimum for the most energy-intensive processes inside pulp and paper mills [8]. The improvement potential afforded by adopting the latest technologies is quantified for each process, amounting to a total opportunity of 48% energy savings over the industry standard. Historical inertia and cheap and available yet carbon-intensive fuel sources have slowed the widespread adoption of these energy-efficient technologies. However, investing in improvements to energy efficiency in each of these areas is unavoidable as the expectations of regulators, investors, and the public to decarbonize operations continue to grow, and unprecedented tax credit opportunities and financial incentives continue to become available.

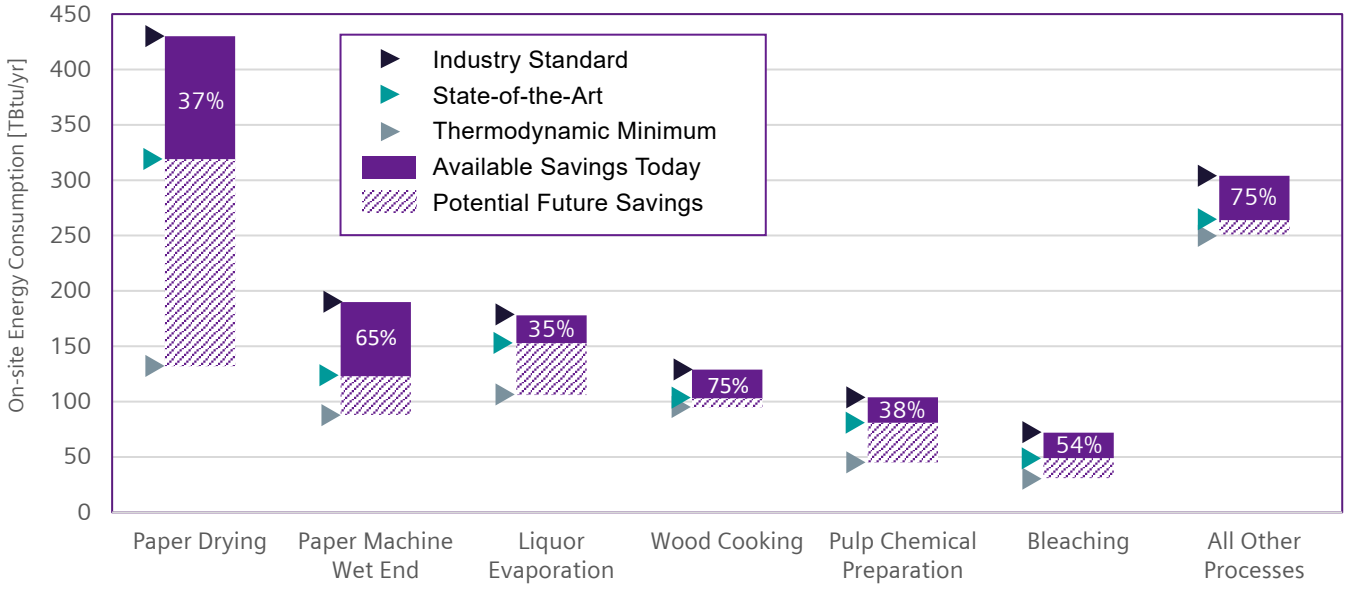


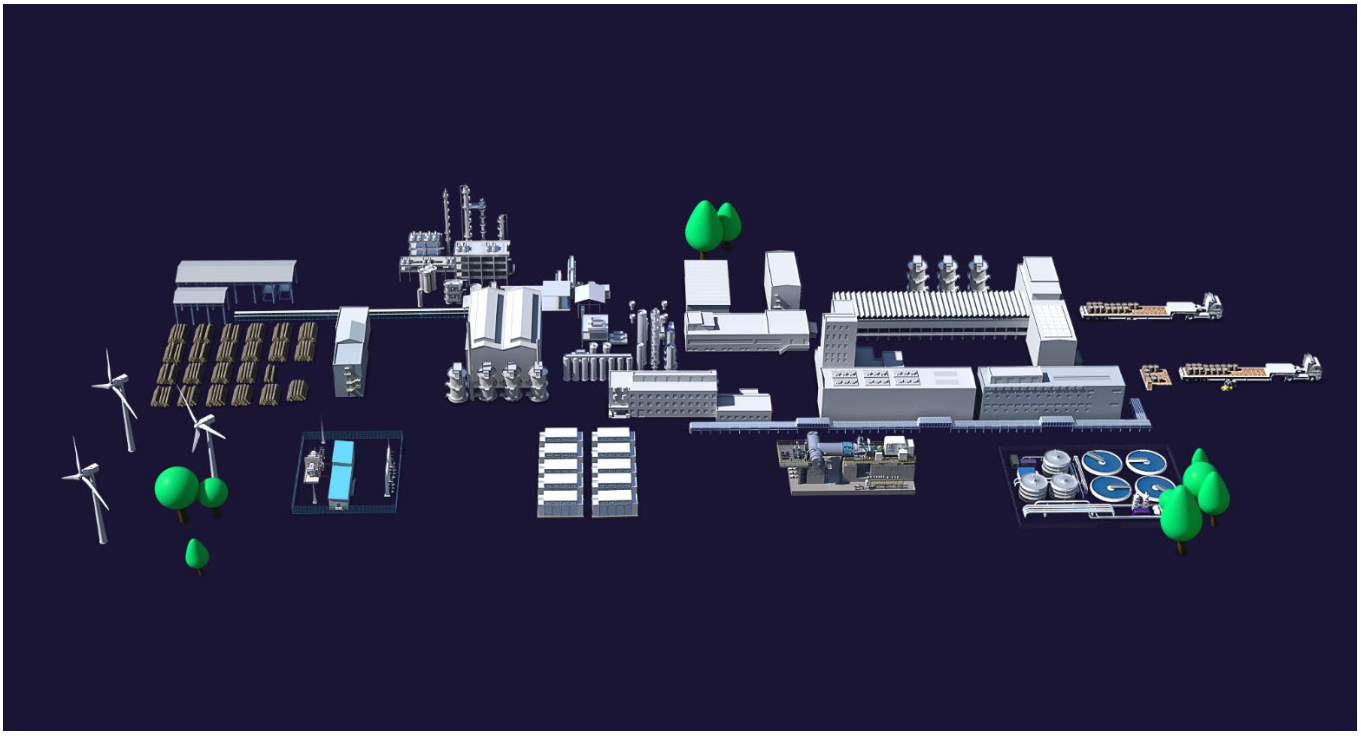

**Figure 1** Current opportunity energy savings bandwidths for processes in pulp and paper manufacturing. Figure adapted from Figure 5-1 of Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing [8]

In addition to technology upgrades, pulp and paper mills can decarbonize their processes and reduce their energy costs by re-evaluating how they generate on-site power and steam. Globally, government incentives such as the U.S. Inflation Reduction Act and the E.U. Green Deal Industrial Plan have begun to incentivize the electrification of heating and processes, power generation from renewables, combined heating and power systems, and waste heat recovery. These energy system opportunities help to reduce scope 1 and scope 2 emissions but may also be eligible for substantial investment and production tax credits. Some of the best practices for capitalizing on these opportunities include:

- Plant hybridization with renewable energy
- Substituting coal with biomass and natural gas as the supplemental fuel source
- Replacing traditional boilers with combined heat and power (CHP) units
- Electrifying heat through electrically powered boilers and heat pumps with waste heat recovery
- Upgrading recovery boiler units to gasification with combined cycle technology
- Improving heat recovery from pulp and paper-making processes, including de-inking, drying, cooking, etc.

Traditional thinking has led to pulp and paper mill assets being purchased and commissioned for a singular purpose. For example, auxiliary boilers and diesel generators have been traditionally built to source auxiliary steam and electricity, respectively. Improvements to the overall mill system have then logically proceeded by upgrading the efficiency of each of its individual assets. Asset upgrades are the central way to improve process energy efficiency. However, mill-wide efficiency, and carbon intensity, will only be significantly improved by considering energy system designs that cogenerate power, steam, heating, and/or cooling, and responsibly manage the energy content available between each of the mill's processes and steam flows. Siemens Energy's Energy System Design studies help industrial customers, including pulp and paper manufacturers, to improve the cost, carbon intensity, and reliability of their energy systems by helping to identify the most robust set of technologies and operating strategies to meet the customers energy needs.

Siemens Energy has helped customers improve the sustainability and profitability of their overall operations by facilitating the recovery of waste streams. For example, Siemens Energy is currently leveraging its expertise in advanced chemical processes with its hydrogen production technology, the PEM electrolyzer Elyzer P-300, to facilitate the synthesis of marine fuel grade methanol from recovered biogenic carbon dioxide and green hydrogen. As a large producer of biogenic carbon, pulp and paper mills are in an excellent position to monetize their waste streams through the introduction of similar green fuel synthesis projects.



# 3 Energy System Design

Siemens Energy has introduced Energy System Design (ESD) to help pulp and paper mills make the right decisions for energy system expansions, upgrades, and new system designs, in light of the need for decarbonized and low-cost energy, the current incentive landscape, and the broad range of technologies available. ESD is a model-based engineering optimization study that selects and sizes energy conversion and storage assets to supply thermal and electrical power to an individual mill or paper machine. Figure 2 summarizes the ESD process.

**Energy System Design Inputs :**

- Energy system loads : electrical, steam (High/Intermediate/Low Pressure), hot water, or chilled water demand on an hourly or sub-hourly basis.
- Options for purchasing and/or selling commodities including pricing : electricity, natural gas, other residuals, etc.
- Local renewable potentials such as solar PV or wind turbine generation profiles
- Local climate conditions to account for asset impacts such as gas turbine or chiller performance.
- Existing mill assets for potential integration within the energy system design.

In addition to these design inputs, Siemens Energy works with customers to understand their technology preferences, the overall objective of the study, and what constraints must be considered. Traditionally, customers are looking for energy systems with a minimum total cost of ownership, but ESD studies can also target improved carbon emissions, primary energy use, energy-system specific water consumption or other attributes, and any combination of these.

Once the customer's energy needs, targets, and site-specific boundary conditions are thoroughly understood, a collection of energy conversion and storage technologies is defined and modeled regarding performance and cost. Each technology is then included as an option within an optimization model. The model evaluates many different collections of these, including their interconnections, to identify the most competitive energy system and asset dispatch strategy for powering the mill.

**Energy System Design Results :**

- Most suitable set of technologies (assets)
- Optimized capacity for each asset
- Most suitable dispatch strategy for each asset

ESD study results are subject to the evaluation period (single or multiple representative year(s)) and provided model data. Since each input to the study is subject to uncertainty, a collection of scenarios is strategically defined, and a few parameters are selected to inform a collection of sensitivity analyses. These sensitivity analyses help identify the most robust possible energy system design against a mill's requirements, targets, and the uncertainty of future information.

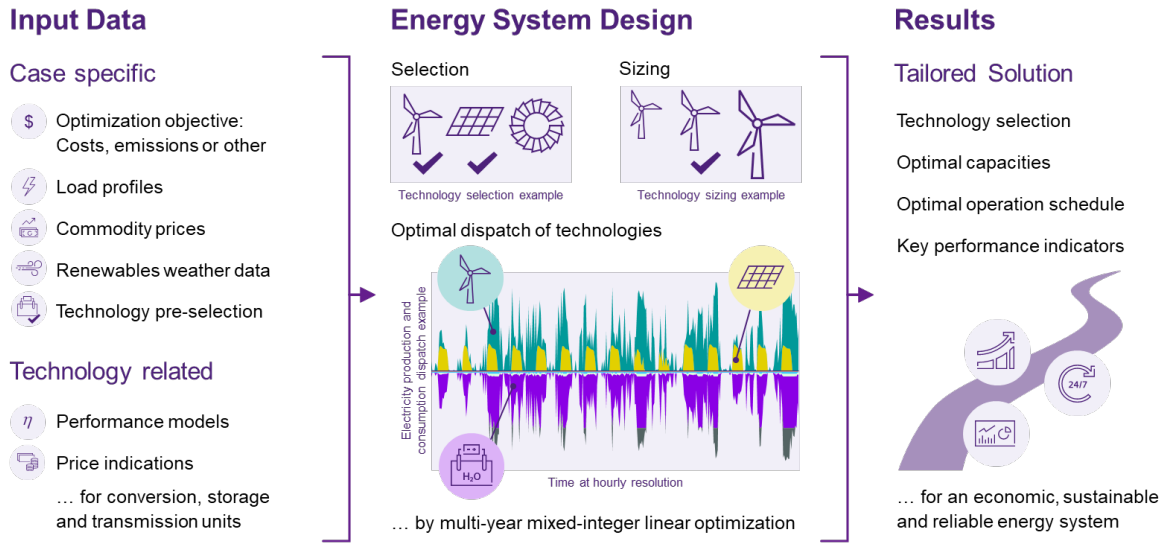



**Figure 2** Energy System Design is a model-based, optimized selection, sizing, and dispatching of technologies to best comprise an energy system.

# 4 Case Study : Cost-optimal decarbonization of a paper machine

Siemens Energy has worked with pulp and paper customers to reduce the cost and carbon emissions of mill energy systems. An ESD study was performed to help one such customer who was considering expanding their paper-production capacity by adding an additional paper machine. The additional electrical and steam demand was estimated at 40 $MW_e$ and 85 $MW_{th}$, respectively. The customer was investigating on-site generation in order to improve power and steam supply security and to take advantage of existing tax credit opportunities. Siemens Energy was tasked with producing a collection of turnkey solutions for power and steam, which included not only the lowest cost option but also those which reduced carbon emissions and the cost associated with each. The presented case study is a simplification of the complete study performed for the customer. The results are anonymized and do not directly reflect the customer's actual proprietary data and study results.

## Reference Case

The ESD study began by establishing a reference case, to both demonstrate the capabilities of Siemens Energy's modeling tools and to establish a baseline for comparing all other energy system designs. The customer's originally proposed energy system design provided steam and power to the new paper machine using a gas boiler and a combined cycle power plant, as shown in Figure 3. The combined cycle power plant includes a gas turbine engine with an auxiliary burner, a heat recovery steam generator, and a high-pressure (HP) turbine. The gas turbine and HP turbine connect to a generator to produce electricity. A small steam turbine converts intermediate pressure (IP) steam into electricity and lower pressure process IP steam for the mill. A grid connection facilitates the purchase and sale of low-cost and excess power, respectively.

The reference system was modeled using Siemens Energy's own optimization tool and verified to estimate system performance within 0.2% of the customer's expected performance based on the new paper machine's loads, assets' performance, and costs. Once verified, this energy system model was adapted to represent the expected electrical and steam loads of the prospective paper machine. In addition, a tax credit for combined heating and power (CHP) capacity was considered alongside tax penalties for excessive non-CHP gas utilization. This energy system design represents the otherwise expected "business-as-usual" expansion of the existing energy system and, therefore, establishes the reference baseline for comparing all other system designs developed by Siemens Energy.

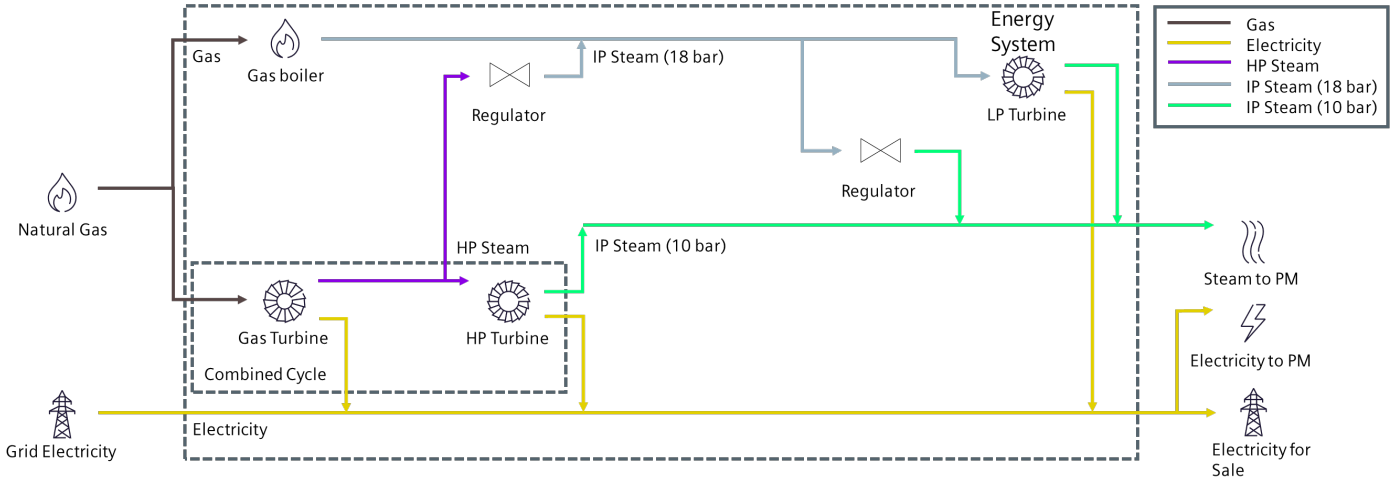



**Figure 3** Reference system as a baseline for comparison to all other energy system designs.

## Energy System Design Optimization

Having established both a reference case and agreement on the customer's energy needs, targets, and site-specific boundary conditions, a set of energy conversion and storage technologies was defined and modeled with respect to performance and cost. The complete collection of energy system design options is shown in Figure 4. In addition to the assets included in the reference system, the ESD study considered:

- Green (carbon neutral) fuel
- Cogeneration using an open cycle gas turbine with a heat recovery boiler and auxiliary firing
- Combined cycle power generation using a gas turbine, heat recovery boiler, auxiliary firing, and an HP turbine.
- Electric boilers
- Solar photovoltaic (PV) and wind turbine power generation
- Steam storage and compression and battery energy storage
- Heat pumps for converting low-temperature heat from gas turbine exhaust or paper machine waste heat to high-temperature heat or steam. Heat pumps can offer the added benefit of de-humidifying and cooling exhaust flows from other areas in the mill. The recovered condensate may be reused to reduce the mill's total water consumption, and the cooler, dryer exhaust may improve other environmental emissions properties.

These technologies are considered based on their potential to positively interact within the system, as well as their commercial maturity and fit for the industry. Performance models define conversion efficiencies between incoming and outgoing energy or material streams, capacity and energy limitations, ramp rates, and other properties. Cost models define investment costs, operation and maintenance costs, and tax opportunities.

The optimization environment was then used to identify the lowest cost system by comparing many combinations of the available assets, the interconnections between them, and their operation. An additional constraint ensured a minimum amount of backup steam capacity to be always available across the energy system. The next step in the ESD study considers "cost-optimal" energy system designs against the uncertainty in the study's inputs.

The results in this whitepaper are simplified from the actual study performed in that only a single IP steam is delivered to the paper machine and only the combined cycle power plant is considered for on-site power generation.

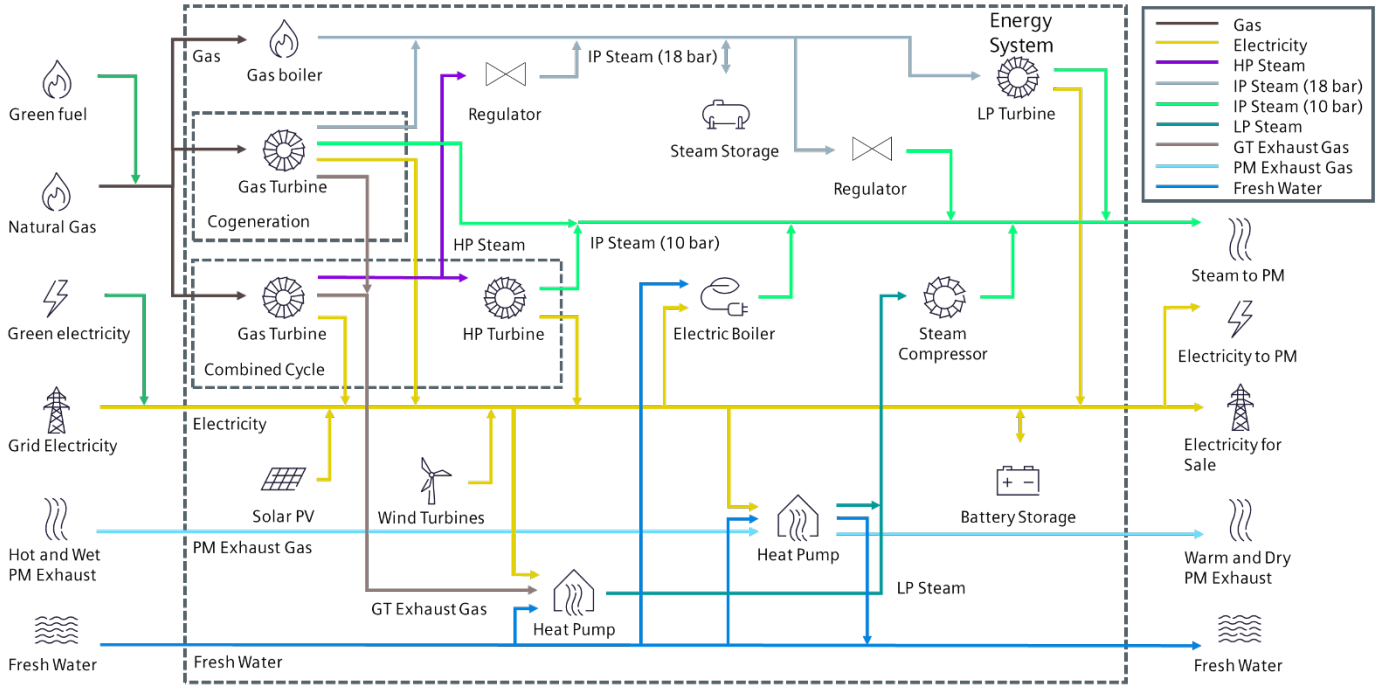



**Figure 4** Complete optimization design space including all considered technologies.

## Sensitivity Analysis

Although individual optimization results may be exciting, to select the overall best design, it is important to understand the impact of uncertainty in the ESD study's inputs on the study's results. The most variable input to this specific study was the current and future price of electricity. Therefore, a collection of twelve electricity purchase price scenarios were considered, each containing a one-year hourly forecast. Each scenario is shown in Figure 5 on a period-averaged basis for clarity. Sale of electricity was assumed to be available at a rate just below the real time hourly purchase price throughout the study.

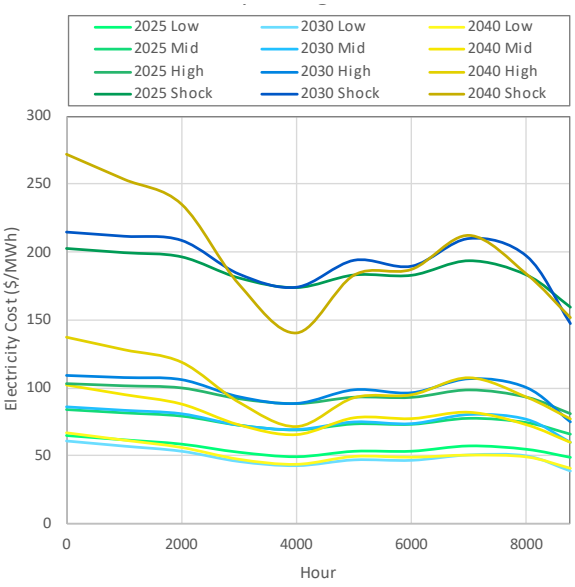



**Figure 5** Period-averaged electricity pricing scenarios.

The complete model was optimized to find the lowest cost energy system across each of the twelve electricity pricing scenarios. In every case, electricity was purchased from and sold to the electrical grid. Three Siemens Energy gas turbine generators were considered in the 30-60 MW range, with the SGT-800 gas turbine delivering the lowest cost option across all twelve scenarios. Across the twelve electricity pricing scenarios considered, six unique energy system designs were identified as cost-optimal in at least one of the scenarios. These six energy system designs, including the sized capacity of the included assets, are summarized in Table 1.

To determine which of the six designs is the best decision for powering the new paper machine, each were evaluated against all twelve electricity pricing scenarios. Within each evaluation, an individual design optimized its asset dispatch to minimize the system's overall cost. The result of this sensitivity analysis is a distribution of the estimated total cost of ownership and $CO_2$ emissions of each of the six designs across the range of future scenarios. The Reference Design was evaluated in the same way for comparison. Figure 6 shows the results of this sensitivity analysis. All six energy system designs significantly outperform the Reference Design, offering, on average, 17% savings to both system cost and carbon emissions. Design 4 offers the largest single scenario benefit with 22.1% cost savings while accomplishing a 26.8% reduction in carbon dioxide compared to the reference case in the 2040 high electricity rate scenario. On the other hand, Design 5 offers the estimated lowest cost, and second lowest $CO_2$ emissions and average standard deviation across all scenarios considered, making it a robust energy system against all future scenarios. Figure 7 shows Design 5 for comparison to the full optimization superstructure shown in Figure 4.

**Table 1** Comparison of cost-optimal designs and references.

| | | Designs | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Ref | 1 | 2 | 3 | 4 | 5 | 6 |
| MW | SGT-700 (CCPP) | 34 | 0 | 0 | 0 | 0 | 0 | 0 |
| | SGT-800 (CCPP) | 0 | 57 | 57 | 57 | 57 | 57 | 57 |
| | HP Turbine | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| | LP Turbine | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |
| | PV | 0 | 0 | 0 | 0 | 0 | 1.74 | 0 |
| | Wind | 0 | 0 | 0 | 2.5 | 2.5 | 2.5 | 2.5 |
| t/h | Electronic Boiler | 0 | 104 | 104 | 104 | 104 | 52 | 52 |
| | Gas Boiler | 208 | 52 | 104 | 52 | 104 | 104 | 104 |
| | Heat Pump - PM Heat Recovery | 0 | 52 | 52 | 52 | 52 | 52 | 52 |
| | Heat Pump - GT Heat Recovery | 0 | 0 | 0 | 0 | 0 | 0 | 20 |

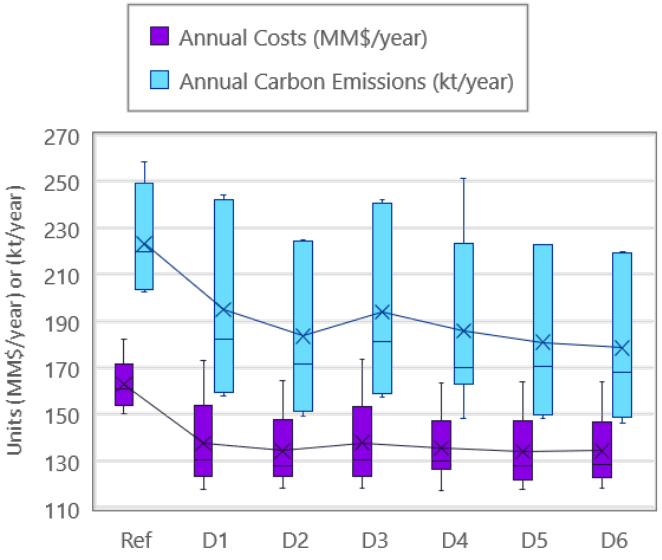



**Figure 6** Sensitivity analysis of all six cost-optimal designs.

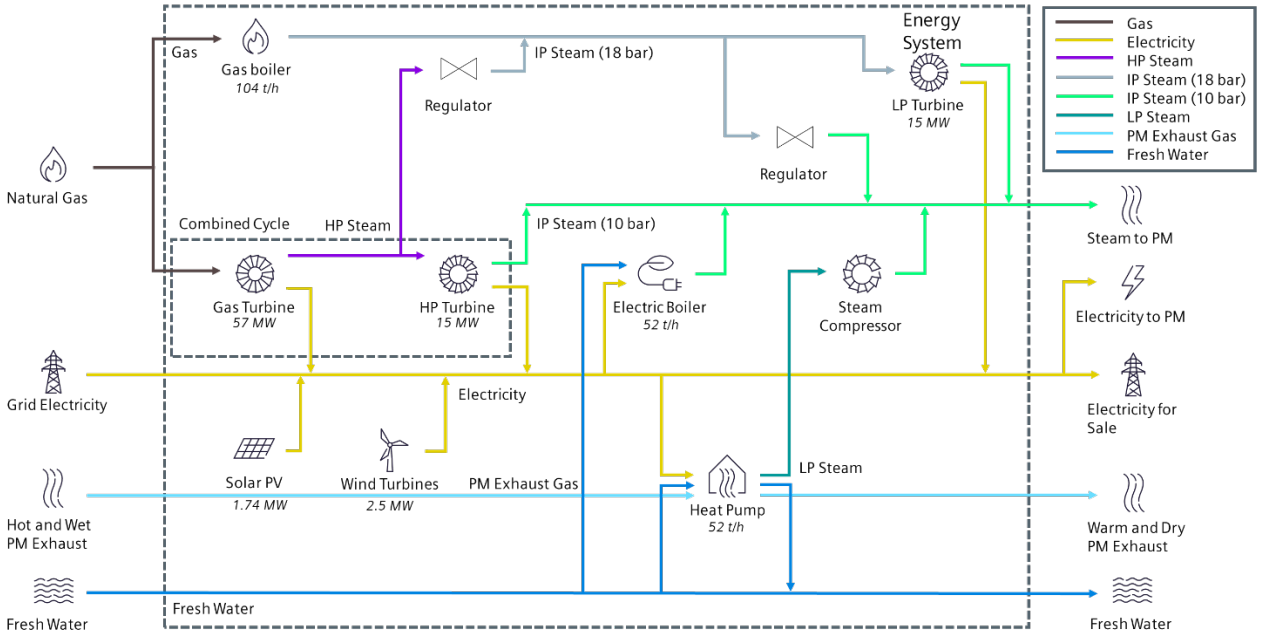



**Figure 7** Design 5 provides the greatest cost benefit across all the future scenarios considered.

## Dispatch Profile

Each optimization exercise conducted within an ESD study identifies the strongest collection of assets and the best dispatch strategy for operating these on an hourly or sub-hourly basis across the modeling period. Figure 8 compares the recommended dispatch profile for the Reference Design to the cost-optimal Design 5 for a single week. As discussed before, the selection and sizing of assets within a design, as well as the operating strategy directing the dispatch of these assets, are what define a specific energy system design. The dispatch profile determined within each evaluation is highly dependent on the electricity price scenario being examined, and the paper machine's steam and electricity load profiles.

In the Reference Design, a combined cycle gas turbine is used to produce electricity and steam from natural gas in some cases while a grid connection and a gas boiler are used to source electricity and steam in other cases when it is more economical. For example, at low electricity and steam demands or low electricity prices, gas boilers are used to produce steam while electricity is purchased from the grid. When the electricity price is higher, the gas turbine is operated alongside the gas boiler to meet steam and power demands, with excess electricity being generated for sale to the grid.

In the cost-optimized Design 5, a combined cycle gas turbine is joined by a grid connection, wind power, solar PV power, and a collection of steam turbines for generating electricity, and a gas boiler, auxiliary burner, heat pump, and electric boiler for generating steam. The capacity of each of these units is optimized for cost, as shown in Table 1. Here, at low electricity prices, steam is generated using the heat pump in addition to the gas boiler while electricity is drawn from the grid. At medium electricity prices, the gas turbine is operated to produce electricity and steam. Excess electricity is generated to drive the heat pump and an e-boiler to supply additional steam. This combined utilization of the units prevents peaks in gas or electricity draw, avoiding demand charges. At high electricity prices, the gas turbine is operated to produce electricity and steam. The gas boiler and e-boiler assist with steam production. Although the heat pump more efficiently converts electricity into steam, it is limited by its minimum operating part-load and therefore is replaced by the e-boiler for steam generation in this condition. Including the heat pump, e-boiler, wind, and solar assets alongside the gas turbine, steam turbines, and boilers allows for more strategic operation in response to real-time electrical and steam loads and electrical pricing. A diverse set of assets also offers a more flexible system for minimizing actual operating costs across the range of possible future scenarios.

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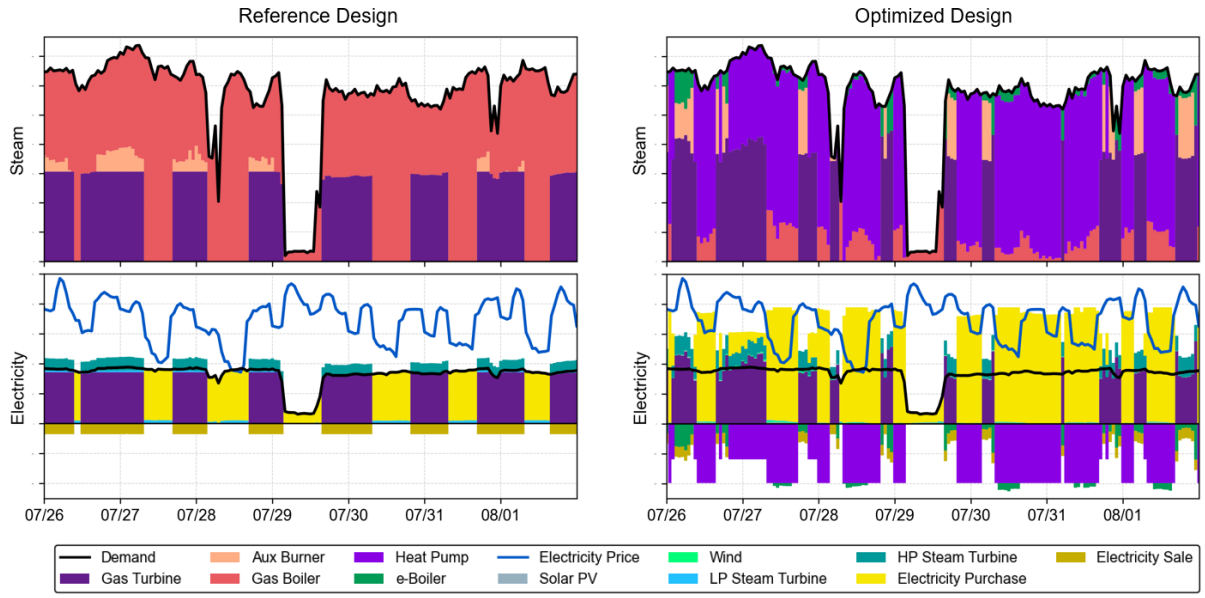



**Figure 8** Hourly asset dispatch profiles.

## Decarbonization

The study thus far has successfully identified a very strong candidate energy system for supplying the expanded mill with the lowest cost electrical power and steam in light of future uncertainties. Next, Siemens Energy helped the customer to identify energy systems which minimize their $CO_2$ emissions in addition to cost. To do this, the complete superstructure shown in Figure 4 was re-optimized with the objective of finding the lowest cost energy system design across a series of constraints on the maximum amount of $CO_2$ emissions allowed. Figure 9 compares the cost and $CO_2$ emissions of the energy system designs developed across progressively more severe $CO_2$ emissions constraints for a single electricity price scenario. Results show normalized values against the original Reference Design.

The ESD study first identified the lowest cost design, as discussed in the previous sections. Within this study, the lowest cost design is Design 4 from the sensitivity analysis, consisting of a combined cycle power plant, LP turbine, wind turbine, electric boiler, gas boiler, and a heat pump to convert mill waste heat into process steam. This is seen visually in Figure 9 by moving down (lower $CO_2$ emissions) and to the left (lower cost) from the Reference Design. In this specific study, in order to reduce the cost-optimal energy system design's $CO_2$ emissions by 10%, new technologies in the form of battery energy storage, a low-cost PV array, and a small amount of low-carbon fuel was required, leading to a slight increase in cost. This energy system design may then be further decarbonized, down to about 70% lower than the cost-optimal design by replacing conventional natural gas with low-carbon fuel. This is seen visually in Figure 9 by moving down (lower $CO_2$ emissions) and to the right (higher cost). At this point, additional higher cost PV energy generation, and flue gas waste heat recovery through a heat pump are required to continue reducing the system's $CO_2$ emissions. Finally, to completely eliminate the system's $CO_2$ emissions, green fuel must completely replace conventional natural gas. This result considers hourly time-matched $CO_2$ emissions accounting and exemplifies a so-called 24/7 carbon-free energy system design. These results are specific to the unique boundary conditions and requirements considered in this study, but demonstrate how powerful of a tool an ESD study can be for decarbonization pathway planning at the mill or fleet level. It is possible that under different conditions, for example with the consideration of markets for renewable energy certificates (RECs) or Guarantees of Origin (GO) for produced electricity, a different specific pathway to decarbonization would likely emerge. ESD helps stakeholders understand the actual costs of reducing $CO_2$ emissions.

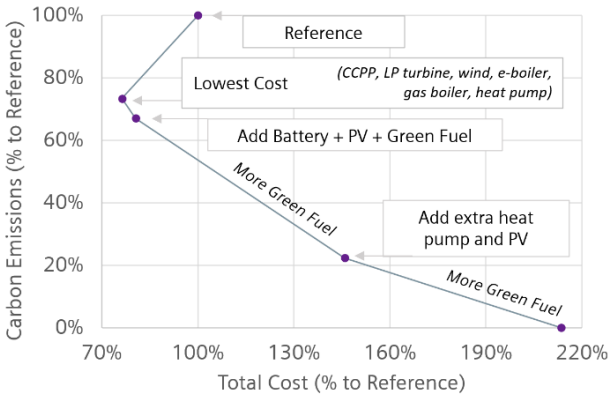



**Figure 9** Estimation of $CO_2$ emissions vs cost of energy system designs.

# 5 Conclusion

Siemens Energy has introduced Energy System Design as a powerful tool to deliver its customers concepts for turnkey energy system solutions to optimize the affordability, reliability, and sustainability of current and future pulp and paper mills tailored to individual customers demands.

This whitepaper discussed energy and carbon management technologies, practices, and opportunities within pulp and paper mills. In addition, a case study detailed the actual deployment of Energy System Design toward the development of the energy system needed to drive a paper machine expansion. The cost optimization study identified energy system designs that consistently outperformed the original Reference Design alternative by reducing cost and carbon emissions by an average of 17%. In one considered future scenario, a cost-optimal design identified in the study offered cost savings of 22.1% while emitting 26.8% less carbon than the Reference Design.

Each energy system design consists of its included technologies, the interconnections between these, and the dispatch, or operating strategy, of each. Dispatch profiles are included to demonstrate the operational differences and opportunities between a cost-optimal design and the reference system. Multiple energy system designs are discussed with their sensitivity to uncertainty in the studies' assumptions and information. Finally, a decarbonization pathway is delivered by identifying cost-optimal energy system designs with progressively lower carbon emissions, culminating in a design which is a so-called 24/7 carbon-free system. This exercise offers customers a practical tool for understanding the cost of decarbonization and what technologies and operating strategies may be required to completely decarbonize their energy systems.

Energy System Design supports the optimization of energy systems for industrial applications. This powerful tool delivers concepts for turnkey energy system solutions complete with technology selection, sizing, and operation within one integrated optimization procedure. A successful energy transition requires balancing affordability, reliability, and sustainability. Siemens Energy works with its industrial customers to maximize each of these in their current and future energy systems by identifying robust energy system designs, guiding cost and environmentally positive waste management strategies, and delivering the world's most efficient industrial energy technologies.

## Source-list


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Siemens Energy
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Freyeslebenstrasse 1
91058 Erlangen
Germany

Siemens Energy Inc.
4400 N. Alafaya Trail
Orlando, FL, 32826, USA

For more information, please visit our website:
https://www.siemens-energy.com/global/en/home/products-services/service/energy-system-design.html

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