Heating Technologies Enabling Fossil-Free Galvanizing With Zero Emissions

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Sustainability has become a critical concern in the global steel industry. As steel production is inherently resource-intensive and generates significant emissions, the implementation of sustainable practices is crucial to mitigate its ecological footprint. This article explores the current state and future prospects of sustainable galvanizing technology, a vital process for enhancing steel's durability by applying a protective zinc coating. Finally, the article presents case studies of fossil-free galvanizing implementations with zero emissions in the U.S. and abroad, illustrating how these initiatives not only comply with stringent emission permits but also contribute to a competitive advantage in the market.

Introduction

In the steel industry, managing emissions is crucial due to the high energy consumption and significant carbon footprint associated with steel production. Companies focus on:

- Reducing scope 1 emissions by improving process efficiency and adopting cleaner technologies.
- Reducing scope 2 emissions by sourcing renewable energy.
- Addressing scope 3 emissions by working with suppliers and customers to reduce emissions throughout the value chain.[1]

Companies in the steel industry primarily focus on reducing scope 1 CO_2 emissions. At the same time, there is a particular emphasis on the reduction of NOx emissions, which occur during the combustion of fuels. The recent adjustment of National Ambient Air Quality Standards (NAAQS) by the U.S. Environmental Protection Agency (EPA) results in a limit of 9 $\mu g/m^3$ as an annual mean for particulate matter $PM_{2.5}$.[2] Therefore, there is an effort to reduce the combustion process to minimize scope 1 CO_2 emissions and NOx. This is possible not only in the liquid phase of steel production but also in the downstream process to the galvanized cold-rolled process. There are two main potentials here:

- Combination/simplification of process routes. Examples are the compact strip production (CSP) process (combination of casting and rolling) or heat to coat (combination of pickling and galvanizing; omission of cold rolling).
- Substitution of natural gas–fired heating technologies with electric heating technologies.

Discussion

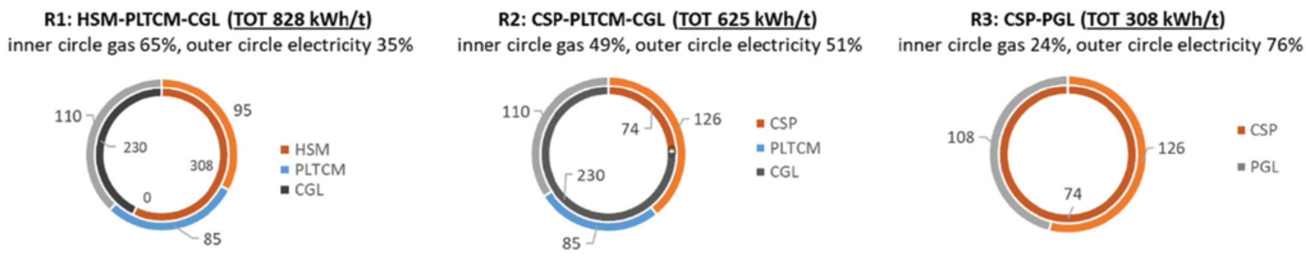
Impact on the Downstream Process Route Regarding CO_2 Emissions

Today, there are three common downstream processes to produce hot-dip galvanized strip (Fig. 1):

- Classically from the hot strip mill (HSM) via the combined pickle line and tandem cold mill (PLTCM) to the continuous galvanizing line (CGL). This has the highest energy requirement with an average of 828 kWh/ton of steel, but has the advantage of being able to produce a very wide and flexible range of products, including outer skin surfaces.

Figure 1

Possible process routes for galvanized steel strip.



- Energy-saving method from CSP via PLTCM to CGL. In this route, the heat input can be reduced from 538 kWh/ton to 304 kWh/ton without changing the heating technology. By casting ever-thicker slabs in the CSP plant, the product range has expanded significantly in recent years.
- Galvanized hot-rolled strip can be produced using the CSP and pickling galvanizing line (PGL) with the lowest energy requirement of 308 kWh/ton.

By removing and combining process steps, up to 60% of the energy can be saved, which has a direct effect on the CO_2 footprint (reduction from 108 kg CO_2/ton through scope 1 to 15 kg CO_2/ton). It can also be seen that by substituting the HSM for the CSP plant, the CGL has the highest specific heat requirement of 230 kWh/ton and is therefore the main source of scope 1 emissions for the hot-dip galvanized steel strip. For this reason, the technological options for avoiding direct emissions during hot-dip galvanizing will be described. Additionally, the PGL will be discussed due to its low energy requirements.

Fossil-Free Processing Line for Production of Cold-Rolled Galvanized Steel Strips

To avoid scope 1 CO_2 and NOx emissions during the annealing and coating of cold-rolled material, it is technically possible to use electrical heating. One of the first CGL plants with pure electrical heating technology is currently being built in northern Sweden. The first coil is due to be produced in 2026.

The target markets for this plant are the automotive and household appliance industries. Consequently, the plant will be able to produce commercial grades, interstitial-free (IF) steel grades and high-strength material up to a tensile strength of 980 MPa. Additionally, it is planned for upgradability to produce third-generation advanced high-strength steel (AHSS) grades in the future, including quenched and partitioning (Q&P), to cover material strengths up to 1,500 MPa.[1]

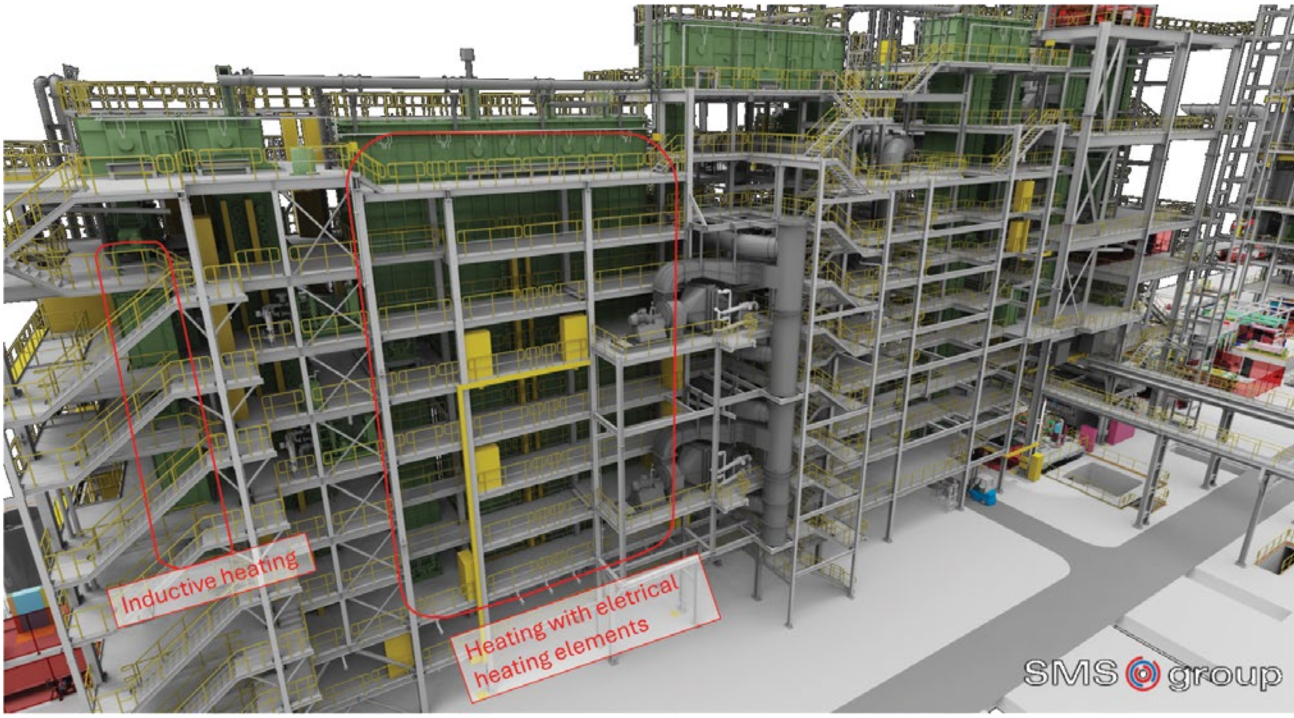
The electric furnace combines induction and electric heating element segments (Fig. 2). The strip can be heated up to 650°C using induction, while it is heated

Figure 2

Fossil-free annealing and galvanizing line to produce cold-rolled galvanized steel strips.

Figure 3

CAD rendering of fossil-free furnace.



and held up to 840°C using electrically heated radiant heating tubes.

The combination of induction and electric heating elements increases the furnace efficiency by 10–15% compared to gas-fired furnaces, mainly due to the avoiding of offgas losses.

Induction Heating: In induction heating, an electromagnetic field generated by a coil current induces an eddy current in the metal workpiece, which flows in the opposite direction of the coil current. This current directly heats the strip due to the electrical resistivity of the material.

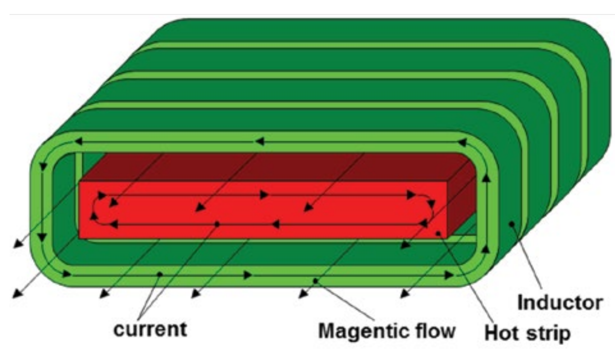
Nowadays, both longitudinal and transverse field inductors are established in industrial applications. For ferritic strips with dimensions between 0.1 and 10 mm, longitudinal field inductors are particularly suitable (Fig. 3), as they ensure homogeneous heating across the strip width.

For this reason, longitudinal field inductors with a total power output of 13 MW are planned for the electric furnace of the CGL to heat a cold strip up to 670°C.

Today, galvanizing lines are characterized by a large spectrum of annealing cycles and product ranges. In conventional furnaces, heat is transferred by means of radiation, so that the strip temperatures will deviate from the targeted temperatures when strip thickness jumps upwards or downwards, as the inert mass of the furnace

Figure 4

Longitudinal inductor principle.

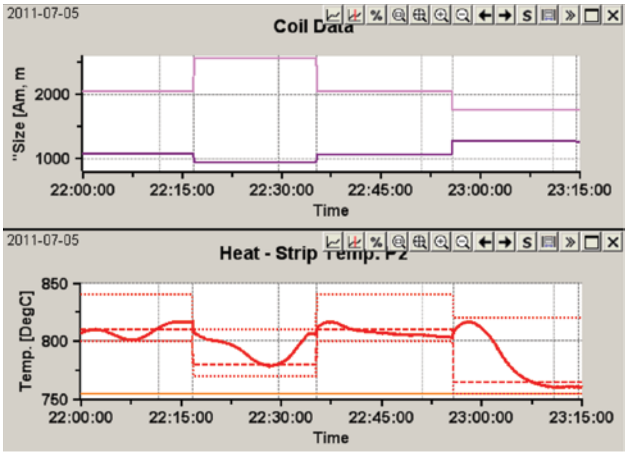


does not permit rapid control. Mathematical models are used to adjust the temperatures in the heating zones so that the narrow tolerance limits are fully utilized in the event of temperature and thickness jumps (Fig. 5). In addition, different grades have different emission coefficients, which means that temperature jumps can also be detected when changing grades. The current process is therefore limited in terms of quality/thickness jumps.

Using induction heating, the heat is introduced directly into the strip. Therefore, it is potentially much easier to compensate for variations in quality and thickness, as the

Figure 5

Typical temperature curve at end of heating within a continuous galvanizing line.



power can be varied continuously and quickly on demand between minimum (a few 100 kW) and maximum power. As a further benefit, the heat input is independent of the strip's emission coefficient.

These advantages allow for temperature windows to be adhered to more closely, and will lead to more flexible production procedures.

Electrical Heating Elements: For strip material, the application of longitudinal induction principle is limited. In particular at the Curie point, ferritic steel changes its ferromagnetic properties to paramagnetic properties. This increases the penetration depth of the current. However, the induced eddy current fields from the bottom and top of the strip must be prevented from canceling each other out. This can only be achieved by increasing the frequency of the alternating voltage. However, typical strip dimensions for paramagnetic steels require frequencies of 300–500 kHz. Today, such frequencies cannot be technically realized with coupling distances of 200–250 mm, which are necessary to avoid problems due to potential strip movement. For this reason, further heating of the strip from 670 to 850°C is realized with electrical-heated radiant tubes with an output of 12 MW.

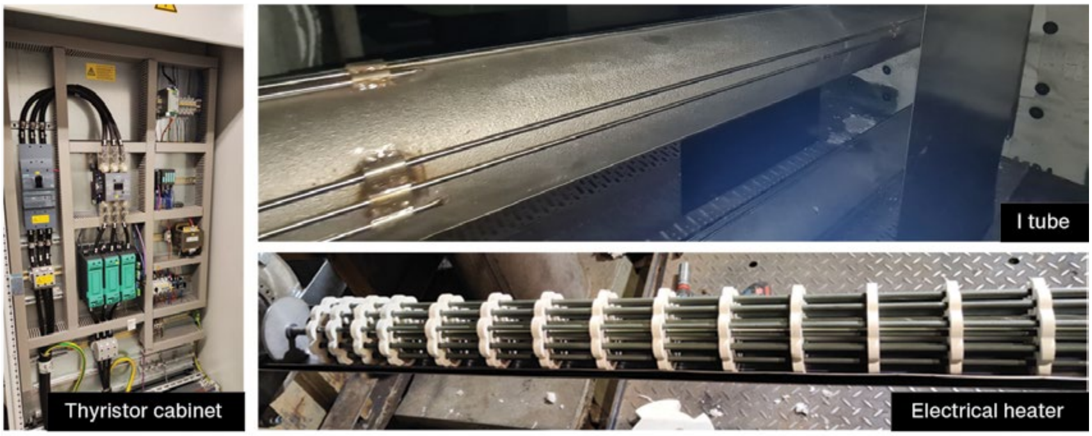
Fig. 6 shows the components of an electrically heated radiant tube. On the left is the thyristor, which provides the electrical current and voltage to power the heating wires shown in the bottom left. The tubes are I-shaped. The heating element is pushed into an I-tube. In contrast to the purpose of atmospheric separation for gas fired tubes, the tube in this case serves as the physical protection of the heating element in the event of a strip break. The main aspects in comparison to the gas-heated tubes are:

- The power regulation of the heating elements is adjustable between 0 and 100%, unlike the gas-fired burners, which do not reach beyond a turndown of 3 in power.
- The heating wire has no physical mechanism benefiting self-protection. If the power is not reduced by the environment, it overheats and its service life is reduced.
- As with the gas-fired pipe, the service life of the pipe is also reduced as the temperature rises. Therefore, the power input from the electric heater must also be limited by the pipe temperature.

For a cost-effective design of the heating element and tube, with consideration of tube and heater temperature limitations, numerical simulations were carried out at SMS. Additionally, a test rig was set up to represent part of a hot-dip galvanizing process. The test rig is shown in Fig. 7.[3] Each heating conductor can be

Figure 6

Components for an electrical heated tube.



powered with up to 60 kW. The power can be controlled by means of a three-phase thyristor. Radiant tubes with a length up to 2,700 mm can be used in the test rig. From the ceiling of the rig's chamber, a series of cooling pipes are inserted to the left and right of the heating elements, which extend to the floor of the chamber. Those are intended to represent the strip in a galvanizing plant. The cooling capacity of each tube can be set individually to simulate narrow and wide strips running on one or two sides.

A key task is to determine the limits and potentials of electric heating technology using the test rig and accompanying simulations. To compare electric radiant heating tubes with gas-fired tubes, temperature distributions were recorded on gas-fired tubes in production facilities. Fig. 8 shows an example of the temperature curve over a typical W-tube. Temperatures in the first leg, where most of the combustion reaction takes place, are up to 100°C higher than in the second leg.

Similar tests were carried out using three electrically heated I-tubes. Here, thermocouples were applied at three positions along the length of the tube. Fig. 9 shows the resulting temperature distribution. The temperature deviation is half as with the gas-fired W-tube. This is also understandable as, in contrast to the gas-fired tube, the heat is emitted evenly over the length of the heated wire's length. Nevertheless, some temperature irregularities can be recognized.

Those can be explained using numerical simulations. Fig. 10 shows an electrically heated tube that absorbs heat above and below the strip. The tube is located in the furnace from left to right. It can be seen that the temperature of both the heating conductor and the tube decreases from left to right. In addition, the surfaces of the tube directly facing the strip are colder than the surfaces where the tubes face each other. The temperature distribution across the pipe is determined by the view factors of the different surfaces. The left part of the tube only sees the strip proportionally, still having the same heat flux density. Hence this tube area needs to be warmer, while the middle part is

Figure 7

Test rig for testing heating elements.

Figure 8

Temperature measurement on gas-fired tubes.

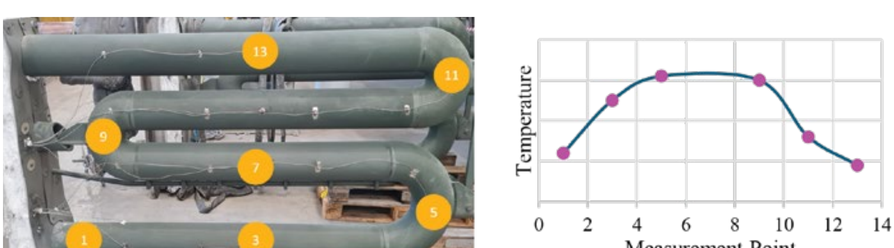


Figure 9

Temperature measurement of electrical heated I-tubes.

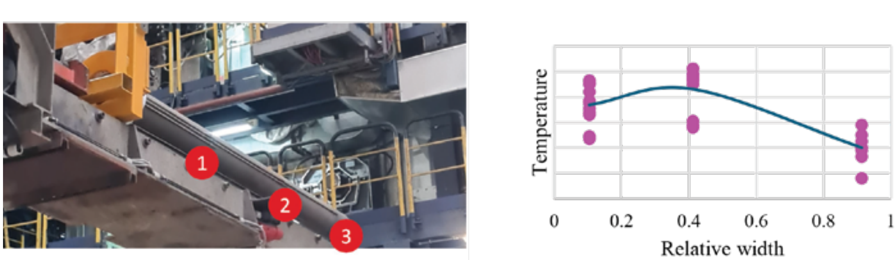
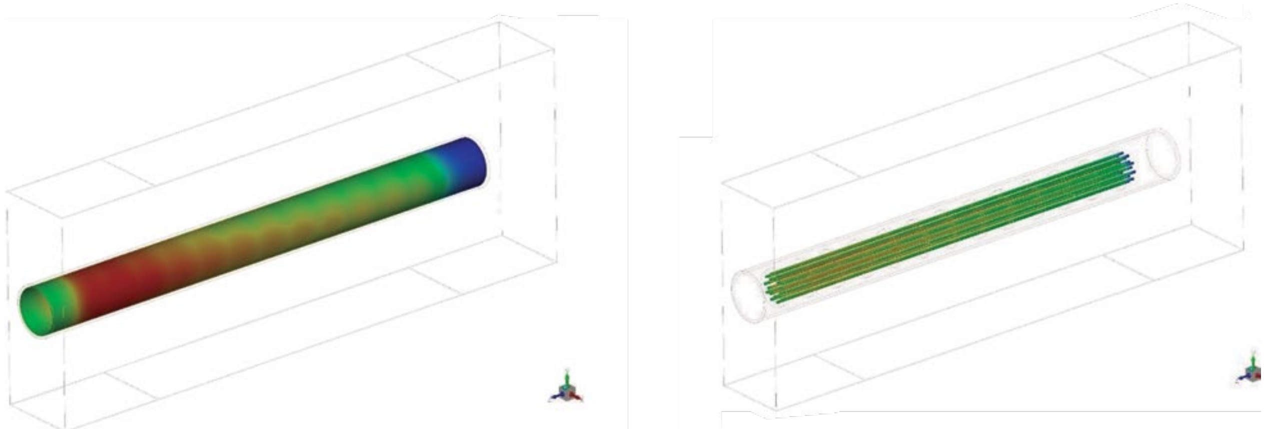


Figure 10

Numerical temperature distribution of electrical heated tube: Tube temperature (a) and wire (b).



(a) (b)

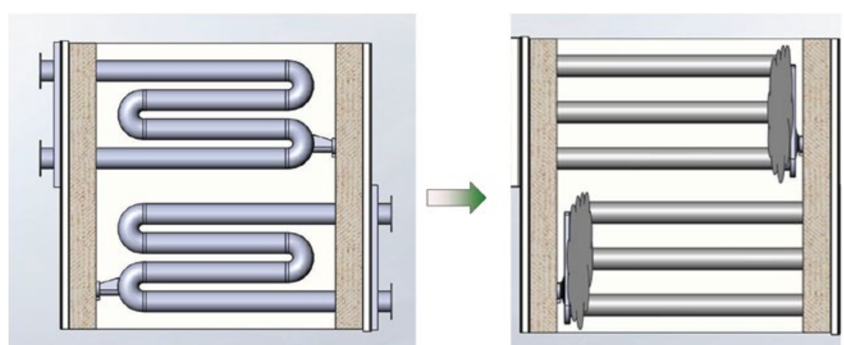
colder due to the stronger influence of the colder strip. The last part of the pipe is significantly colder than the rest of the tube as the heating element does not stretch to the tube's end, which is necessary due to the creep and expansion behavior of the heating elements.

For the dimensioning of the electric radiant tube furnace, it was essential that the calculated and tested limitations of the electrically heated tube are not lowered in comparison with widely used gas-fired radiant tubes. In general, maximum temperatures, quantity and diversity of temperature changes and overall temperature differences as well as the material composition are decisive for the service life of a radiant tube.[3] The comparison of gas-fired tubes to electrically operated tubes result in an arrangement in which a number of three electric heating tubes can replace a gas-fired W-tube (Fig. 11). Due to a thermal efficiency of up to 98% for the electric heating elements to a firing efficiency of around 75% for the gas-fired tubes, the performance of the two heating variants is different. The same heat is transferred into the strip with an output of 3 x 40 kW electric heating power as with a burner power of 160 kW.

Fig. 12 shows the comparison, which has been proven both numerically and in production plants. Due to the smaller areas but the better visibility factors to the strip, the electrically heated tubes have a higher mean temperature, while the maximum temperature is lower due to the more homogeneous temperature distribution.

Figure 11

Numerical temperature distribution of electrical heated tube.



In conclusion, electrically heated radiant tubes can be dimensioned similarly to gas-fired tubes expecting a similar service life. The more homogeneous temperature distribution of the tube also allows higher tube temperatures to be reached, potentially achieving little higher annealing temperatures using the same tube material.

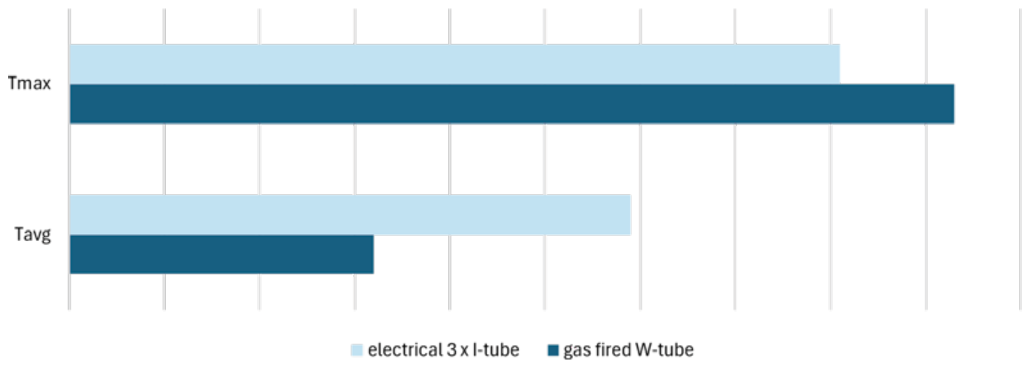
Fossil-Free Processing Line to Produce Hot-Rolled Galvanized Steel Strip

An electrically heated annealing and galvanizing furnace for the processing of cold-rolled galvanized steel strip is a new concept. The exclusive combination of induction systems and electrically powered radiant tubes is unique in this application field.[1]

For more than 20 years, the use of inductive heating systems has been an established approach (Fig. 13) with proven feasibility for the production of hot-rolled galvanized steel strip. Skipping the cold rolling operation

Figure 12

Numerical temperature deviations of electrical heated tubes.



makes the production of galvanized hot-rolled steel more economical in various aspects. One aspect is that the energy required for cold rolling is not to be taken into consideration, and the associated scope 1 and scope 2 emissions do not contribute.[1]

In addition, the heating cycles required to produce hot-rolled galvanized steel strip are only optimized to the requirements defined by the metal coating process, as no plastification effects needs to be compensated. The resulting heat-to-coat process operates at low temperature levels, further reducing scope 1 and scope 2 emissions.[1]

The strip thickness variates between 0.8 mm to 6.5 mm. Here within the induction process is also advantageous compared to a gas-fired process regarding specific energy efficiency. Due to its already described low thermal inertia, this line also enables more flexible production with lower transition losses.

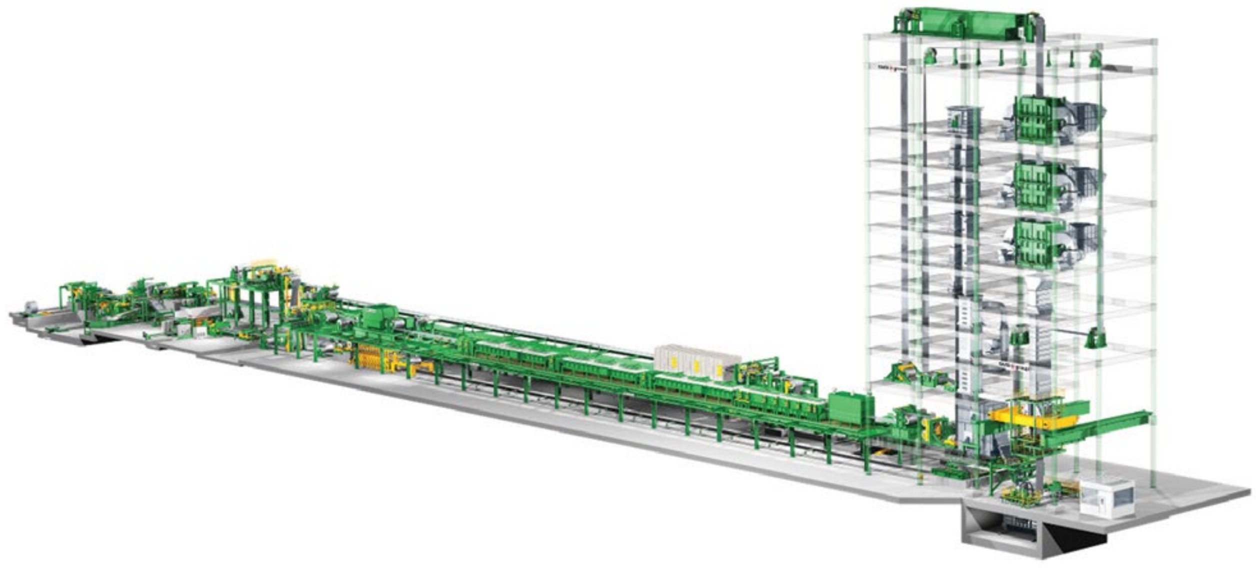
The restart of the galvanizing furnace can be conducted within less than 2 hours.

Conclusions

Significant emission reductions in the production of hot-dip galvanized flat steel are possible by combining or omitting process steps and/or by using fossil-free heating principles instead of fossil fuels for the heating system. By combining processes in the downstream process, the continuous galvanizing lines and pickling galvanizing lines occur as major CO_2 emitters in the downstream process.

Figure 13

Fossil-free pickling and galvanizing line to produce hot-rolled galvanized steel strip.



To reduce direct emission heating here by means of induction or electrically heated tubes offers possibilities.

To conclude, compared to classic heating technology, a combination of induction plus electrically heated elements enables:

- More flexible production in terms of thickness/annealing cycle changes.
- Slightly higher annealing temperatures using the same tube materials.

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