

Electrical energy consumption, enthalpy balance and energy recovery

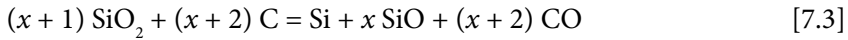
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At first glance, the production of silicon should be easy. There is an abundant amount of silicon dioxide (SiO_2) in nature, which is a source of silicon. Silicon dioxide can be found as quartz or quartzite ores. The challenge in producing silicon or ferrosilicon is to separate silicon from oxygen while using as little energy and reduction material as possible. In current practical terms, the only way to produce silicon is to use solid carbon as a reduction agent. This chapter presents the energy balance for the use of carbon.

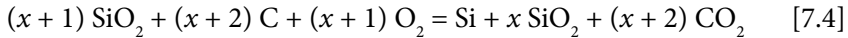
7.1 Stoichiometric analysis of energy balance

The simplified Si furnace

We will first discuss silicon production in the pure system Si–O–C, where we treat the process as a system of stoichiometric chemical reactions. The furnace reaction can formally be treated as a combination of two reactions, Equations [7.1] and [7.2]. Since, as a rule, it is convenient to refer the energy consumption to the silicon that is produced, we combine the reactions so that the coefficient for silicon is 1.



The reaction in the inner zone of the furnace occurs at a temperature of around 2000°C, and the measured temperature of the liquid silicon leaving the taphole is above 1800°C (Tangstad *et al.*, 2021). The liquid cools somewhat from the taphole to the ladle, and has a temperature of around 1600°C in the ladle. After casting, it cools to room temperature, which we set to 25°C. The gases leaving the top of the furnace have a measured temperature of around 1400°C, but can also be lower. Furnace gases are mixed with an excess of air and burned above the charge. This gives an overall process reaction:



In addition, the excess oxygen and nitrogen in the air are heated to the temperature of the waste gas, which is here assumed to be around 150°C. Both the combustion reactions of SiO and CO, and the cooling of cast silicon, give off heat, while the sum of the furnace reactions consumes heat. The heat needed for the furnace reactions is added as electrical energy. All this information is summarised in Figure 7.1, where oxygen introduced as air is identified with the letter *m*. Table 7.1 lists the calculated changes in enthalpy for the various reactions involved when the actual temperatures in and out are included.

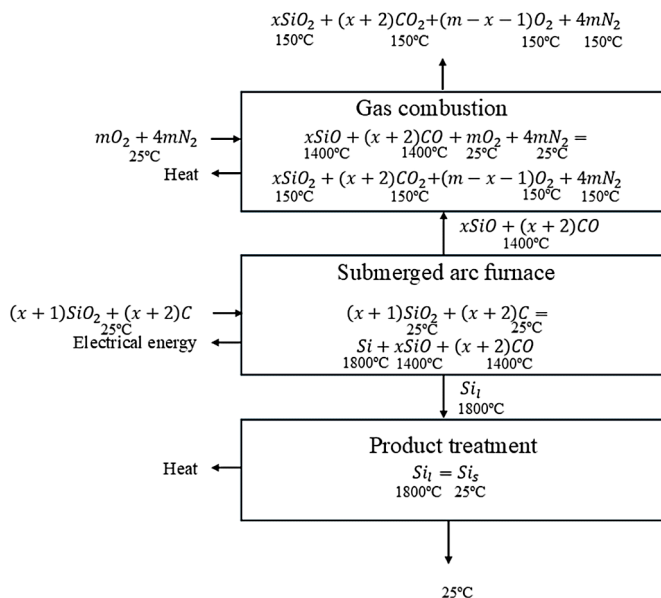


Figure 7.1 Heat and mass flows in the silicon production process for the pure system Si–O–C. The numbers below the chemical symbols give the temperature in degrees Celsius. The temperature indications are based on observations in production furnaces. The total amount of oxygen to the process is m .

Table 7.1 The enthalpy change for some reactions needed to establish an energy balance for the complete silicon process (calculated by HSC Chemistry (Roine, 1997)). The numbers below the chemical species give the temperature in $^\circ\text{C}$.

Reaction	Change of H kJ	Reaction	Change of H kJ
$SiO_2 + 2C = Si + 2CO$ 25 25 1800 1400	877	$Si = Si$ 1800 25	–97.0
$SiO_2 + C = SiO + CO$ 25 25 1400 1400	793	$SiO_2 = SiO_2$ 150 25	–6.3
$Si + O_2 = SiO_2$ 25 25 25	–911	$CO_2 = CO_2$ 150 25	–5.1
$C + O_2 = CO_2$ 25 25 25	–394	$N_2 = N_2$ 150 25	–3.6
$SiO + 0.5O_2 = SiO_2$ 1400 25 150	–852	$O_2 = O_2$ 150 25	–3.8
$CO + 0.5O_2 = CO_2$ 1400 25 150	–322		

By combining the data in Table 7.1, the enthalpy change for each of the three stages in Figure 7.1 can now be calculated as functions of the parameter x , which defines the silicon yield R through the reactions:

$$R = \frac{1}{1+x} \quad \text{or} \quad x = \frac{1-R}{R} \quad [7.5]$$

Heat consumption of furnace reaction

$$= 877 + 793 \cdot x \frac{\text{kJ}}{\text{mol}} \text{Si} \quad [7.6]$$

The solidification and cooling of the product Si will give off heat:

Heat given off in cooling of product

$$= 97 \frac{\text{kJ}}{\text{mol}} \text{Si} \quad [7.7]$$

The gas from the charge of the furnace is mixed with excess air and burns. The heat given off from the combustion step is calculated from data in Table 7.1:

Heat from off-gas combustion

$$= 852 \cdot x + 322 \cdot (x+2) - 3.8 \cdot (m-x-1) - 3.6 \cdot 4m \frac{\text{kJ}}{\text{mol}} \text{Si} \quad [7.8]$$

The waste gas with solid dust still has some energy left when it leaves the combustion zone at 150°C. According to data in Table 7.1, we have:

Heat in waste gas

$$= 6.3 \cdot x + 5.1 \cdot (x+2) + 3.8 \cdot (m-x-1) + 3.6 \cdot 4m \frac{\text{kJ}}{\text{mol}} \text{Si} \quad [7.9]$$

If we look at the process as a chemical reaction, the items above give a complete description of the energy relations. However, if we look at the process from the point of view of energy economy, we must take into account the fact that the process consumes carbon that could have been used as a fuel. Until now, the reference state, where Gibbs energy is zero, has been defined as the

most stable elemental state at 25°C. When considering the energy economy, we set the reference state to the most oxidative state at 25°C. This means that both carbon and silicon will have a certain amount of energy, according to the reactions $C + O_2 = CO_2$ and $Si + O_2 = SiO_2$, respectively. According to data in Table 7.1, we have:

$$\text{Heat value of silicon} = 911 \frac{\text{kJ}}{\text{mol}} \text{Si} \quad [7.10]$$

$$\text{Heat value of carbon} = 394 \cdot (x + 2) \frac{\text{kJ}}{\text{mol}} \text{Si} \quad [7.11]$$

The formulas in Figure 7.1 and the text above can be used in a spreadsheet to produce a table of the heat and mass balance for the complete silicon production process.

In this stoichiometric evaluation of the process, the energy values are reported as $\frac{\text{kJ}}{\text{mol}} \text{Si}$, which is the standard base for thermochemical calculations.

For metallurgists, the unit $\frac{\text{MWh}}{\text{MT}}$ (MT = metric ton) is more familiar,

and we can recalculate the result by the formula

$$\left[\text{numerical value in } \frac{\text{MWh}}{\text{MT Si}} \right] = \frac{1000000}{M_{\text{Si}} \cdot 3600} \cdot \left[\text{numerical value in } \frac{\text{kJ}}{\text{mol Si}} \right] \quad [7.12]$$

where $M_{\text{Si}} = 28.09$ is the atomic weight of Si. The energy and material balance for the silicon process is given for several values of the recovery R in Table 7.2. The table reports values for the production of 1 MT of silicon, which is the most common basis for reporting consumption in the industry. However, sometimes we want to use another basis, e.g. a given electric load or a given consumption of quartz. Such a recalculation is simply a change of scale of the results in Table 7.2. If we want to calculate the silicon production for a 20 MW load at a silicon recovery of 0.90, for example, we can calculate this from the results in Table 7.2:

$$\text{Production of Si} = \frac{1.0 \cdot 20}{9.54} = 2.1 \frac{\text{MT}}{\text{hour}}$$

The results are given in Table 7.3.

As a summary, the specific energy consumption will decrease with increasing silicon yield R , as there are large energy costs in making SiO gas in addition to liquid silicon. This has been shown in Table 7.2 and Table 7.3 and graphed in Figure 7.2, and is also summarised in equation [7.13]. With increasing silicon yield, R , the carbon consumption per tonne of silicon will also decrease, as less carbon will be used to produce SiO gas. However, the carbon consumption per tonne of SiO₂ will increase, as we will use less carbon per tonne of SiO₂ to produce SiO gas than liquid silicon, as seen in Figure 7.3. In the examples shown above, the liquid silicon leaves the furnace at 1800°C, and the CO and SiO gas at 1400°C. If the temperatures change, the energy consumption will also change; however, this effect is minor. Assuming the metal leaves the furnace at 1600°C instead of 1800°C, the energy consumption will decrease by 54 kWh/ton of Si, that is 0.45–0.62%, depending on the silicon yield. If the gas temperature changes from 1400 to 1300°C, the energy consumption is reduced by 0.8%, that is from 70 to 100 kWh depending on the Si yield.

$$\hat{E}_{Si}(\text{theoretical}) = 853 + \frac{7818}{R} \left[\frac{\text{kWh}}{\text{tonne Si}} \right] \quad [7.13]$$

Where $\hat{E}_{Si}(\text{theoretical})$ is the theoretical specific energy consumption and R is the Si yield, where $0 < R < 1$.

Table 7.2 *Material and energy balance for the silicon production process in the pure system Si–O–C. Data for the production of 1 MT Si.*

Silicon recovery R		1	0,9	0,8	0,7
Reaction parameter x		0,000	0,111	0,250	0,429
Air addition parameter m		2,000	2,223	2,500	2,858
Ratio air/gas production		5	5	5	5
Material balance					
<i>In</i>					
SiO ₂	MT	2,139	2,377	2,674	3,056
C	MT	0,855	0,903	0,962	1,039
O ₂	MT	2,279	2,532	2,848	3,255
N ₂	MT	7,976	8,862	9,970	11,394
<i>Out</i>					
Si	MT	1,000	1,000	1,000	1,000
CO ₂	MT	3,133	3,307	3,525	3,805
SiO ₂	MT	0,000	0,242	0,544	0,932
O ₂	MT	1,139	1,266	1,424	1,628
N ₂	MT	7,976	8,862	9,970	11,394
Energy balance:					
<i>In</i>					
Chemical energy in C	MWh	7,79	8,22	8,76	9,46
Electrical energy	MWh	8,67	9,54	10,63	12,02
<i>Sum in</i>	<i>MWh</i>	<i>16,5</i>	<i>17,8</i>	<i>19,4</i>	<i>21,5</i>
<i>Out</i>					
Enthalpy in silicon (cooling and solidification)	MWh	0,96	0,96	0,96	0,96
Combustion and cooling of gas	MWh	6,06	7,33	8,92	10,95
Chemical energy in Si	MWh	9,01	9,01	9,01	9,01
Heat in waste gas	MWh	0,42	0,47	0,53	0,61
<i>Sum out</i>	<i>MWh</i>	<i>16,4</i>	<i>17,8</i>	<i>19,4</i>	<i>21,5</i>

Table 7.3 *Material and energy balance for the silicon process in the pure Si–O–C system – data for production in a 20 MW furnace.*

Silicon recovery		1	0,9	0,8	0,7
Reaction parameter x		0,000	0,111	0,250	0,429
Air addition parameter m		2,000	2,223	2,500	2,858
Ratio air/gas production		5	5	5	5
Material balance					
In					
SiO ₂	MT/h	4,935	4,984	5,034	5,085
C	MT/h	1,973	1,893	1,811	1,728
O ₂	MT/h	5,256	5,308	5,362	5,416
N ₂	MT/h	18,397	18,579	18,766	18,956
Out					
Si	MT/h	2,307	2,097	1,882	1,664
CO ₂	MT/h	7,227	6,934	6,635	6,330
SiO ₂	MT/h	0,000	0,507	1,024	1,551
O ₂	MT/h	2,628	2,654	2,681	2,708
N ₂	MT/h	18,397	18,579	18,766	18,956
Energy balance					
In					
Chemical energy in C	MWh	17,970	17,241	16,498	15,739
Electrical energy	MWh	20,000	20,000	20,000	20,000
<i>Sum In</i>	<i>MWh</i>	38,0	37,2	36,5	35,7
Out					
Enthalpy in silicon (cooling and solidification)	MWh	2,212	2,011	1,805	1,596
Combustion and cooling of gas	MWh	13,980	15,368	16,781	18,221
Chemical energy in Si	MWh	20,780	18,888	16,958	14,989
Heat in waste gas	MWh	0,969	0,985	0,998	1,015
<i>Sum out</i>		37,9	37,3	36,5	35,8

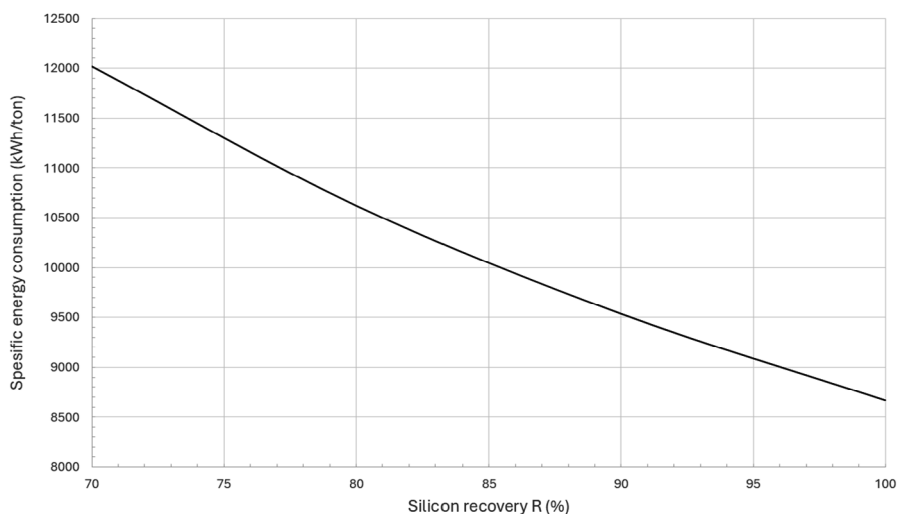


Figure 7.2 Figure showing the specific energy consumption shown in Table 7.2.

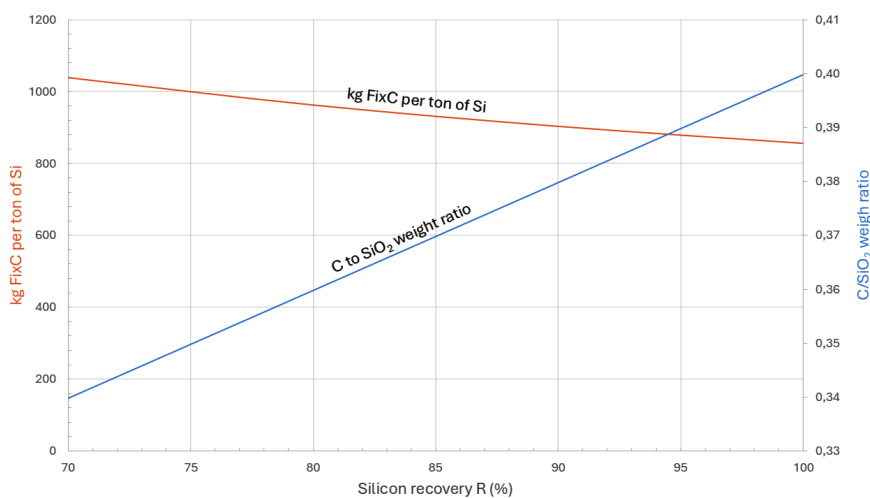


Figure 7.3 Figure showing the theoretical consumption of carbon with increasing silicon recovery.

Temperature in the off-gas

The temperature in the off-gas may be controlled by the amount of excess air. If the SiO and CO gas from the furnace is 1400°C on average, the off-gas temperature can be calculated as a function of the amount of air in the off-gas. This is done by balancing the enthalpy of combustion of the CO-gas and the SiO-gas with air against the specific heat content of the total off-gas. Figure 7.4 and Figure 7.5 show the off-gas temperature in a system with 80% silicon yield (calculated by HSC Chemistry (Roine, 1997)). Note the sharp increase in temperature during the burning of SiO-gas. The qualitative temperature for an industrial process will be commented on in Section 7.7.

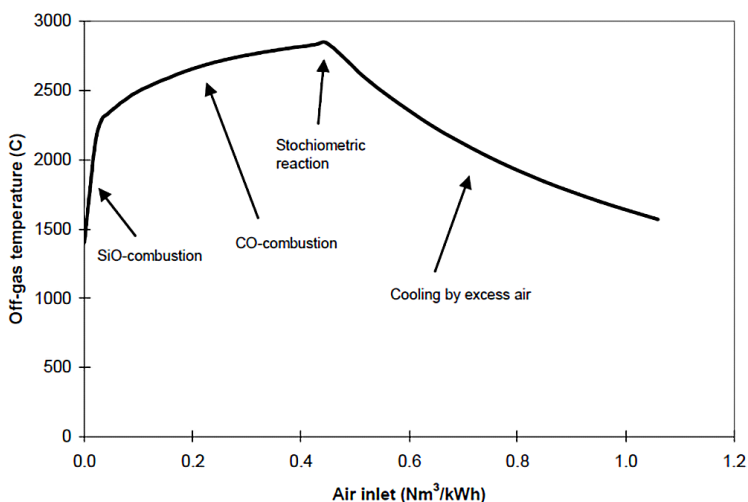


Figure 7.4 The temperature in a theoretical silicon production process with 80% silicon yield. The sharp increase in the temperature during the SiO-combustion is due to the high enthalpy in the SiO-gas and the low total gas volume when a low amount of air is added.

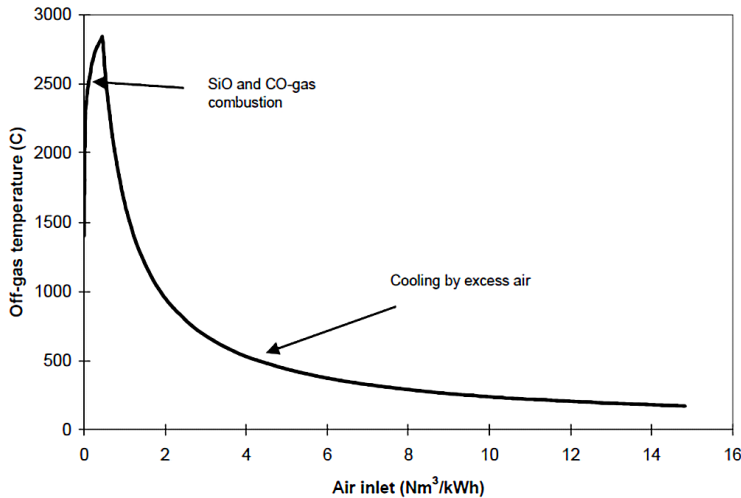


Figure 7.5 The temperature in a theoretical silicon production process with 80% silicon yield. The figure shows the huge amount of excess air needed to control the off-gas temperature (Figure 7.5 is an extension of Figure 7.4).

7.2 The industrial silicon process

The main difference between the theoretical process and an industrial process is related to the following: 1) energy losses from the process, 2) the use of non-pure carbon, 3) carbon losses to the off-gas system and 4) other minor deviations from an ideal process.

Energy losses from the process

To obtain a more realistic energy balance for a silicon process, it is necessary to take the different losses into account. There are several types of energy losses, which may vary from furnace to furnace. These include heat in cooling water equipment, in the off-gas, or as radiation heat from the furnace body. The loss of electric energy occurs because the large electricity supply to the process is delivered by a high current at low voltage from the transformers. Typical currents may be in the order of 100 000 A per electrode, which induces high losses in the electricity supply system. The losses are high in

the transformers, the electricity conductors, and the electrodes. The main energy loss is transferred to the cooling water in the transformers, busbars, and electrode support systems. From the electrodes, some of the loss will be in the form of radiation to the furnace hood or the surroundings.

The theoretical energy calculated above is plotted on the same graph as the results from some industrial furnaces (Figure 7.6) to estimate the effect of the energy loss. The graph shows a discrepancy of 2000–3000 kWh/tonne Si. This difference is mainly due to losses of electric energy that are normally measured at the transformers. To calculate the energy flow for a furnace, it is important to determine where the electric losses take place. For example, irrespective of whether the electric energy losses in the transformers are converted to cooling water losses or to heating the local surroundings of the transformers, this energy must be considered lost from the process. However, some of the electric energy loss is resistance heating of the electrodes, and some of this energy will be found as thermal energy in the off-gas from the process.

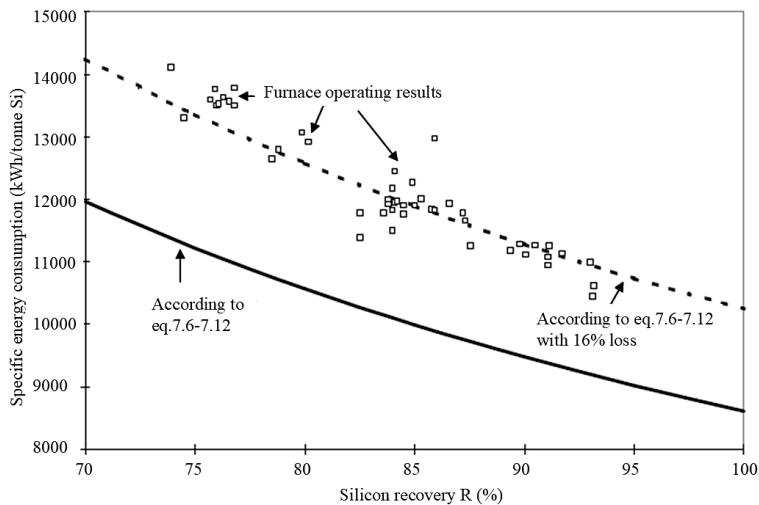


Figure 7.6 Measured and calculated energy requirements for a silicon process as a function of silicon recovery to the metal. The dotted line represents the theoretical energy requirements with an energy efficiency = 0.84.

An energy yield factor (e_y) may be introduced to describe the energy efficiency. This factor states how much electric energy the process receives compared to the total electric energy delivered to the process. The energy yield depends on the design of the furnace and the operational parameters. As seen in Figure 7.6, inserting an energy yield factor of 0.84 seems to provide a much better correlation between silicon recovery and specific energy consumption. The total specific energy consumption can then be calculated by expanding Equation [7.13] to Equation [7.14]:

$$\hat{E}_{Si} = \frac{1}{e_y} \left(853 + \frac{7818}{R} \right) \left[\frac{kWh}{tonne Si} \right] \quad [7.14]$$

where $\hat{E}_{Si}$ is the theoretical specific energy consumption, R ($0 < R < 1$) is Si yield, and e_y ($0 < e_y < 1$) is the energy yield factor.

The reason for the variations in the industrial results may be that different furnaces have differing energy yield factors, or simply that there is inaccuracy in the figures.

Carbon – volatile compounds

In the theoretical calculations above, the reduction was assumed to be done with pure graphite. Normally, this is not the case in the production of silicon and silicon alloys. Coke, coal, charcoal and woodchips are the usual carbon sources. The amount of fixed carbon in the reduction agents is of interest to the process. In addition, coke and coal introduce other elements than carbon. The volatile hydrocarbons are of particular interest, as they add extra chemical energy to the input of the process. Coke normally has a low content of volatile hydrocarbons, often 0–10% weight. Charcoal typically contains 10–20% volatiles (Myrhaug, 2003; Smith-Hanssen, 2022). The volatile hydrocarbons will increase the amount of energy in the off-gas system, because they will burn together with the CO gas from the process. Table 7.4 gives examples of carbon materials used in the silicon production process.

The use of non-pure carbon will change the process in several ways:

- Accompanying volatile hydrocarbons add extra chemical energy
- Carbon materials contain ash with oxides such as aluminum oxide and calcium oxide which require energy to be reduced
- Water content must be driven off
- The accompanying extra mass may be beneficial to SiO-condensation

Table 7.4 *Examples of properties of carbon materials used (Andersen, 2023).*

Proximate		Coal	Charcoal	Coke	Woodchips
Moisture	%	8,17	1,4	6,31	6,68
FixC (d)	%DW	57,6	79	90,5	14,6
Volatiles (d)	%DW	40,4	17,7	6,64	84,2
Ash (d)	%DW	2,04	3,32	2,84	1,16
Ultimate					
C (d)	%DW	78	83	89,3	50,7
N (d)	%DW	1,58	0,39	1,78	0,2
O (d)	%DW	12	9,6	3,83	41,4
H (d)	%DW	5,79	3,71	1,83	6,48
S (d)	%DW	0,52	<0.1	0,42	0,11
Energy content					
NHV	kWh/kg	7,74	8,3	8,05	2,69
NHV/FixC	kWh/FixC	15,06	11,02	10,15	33,52

The large variation in the volatile content and the fixed carbon in the various carbon sources is seen in Table 7.4. This variation is important for the total energy in the combustion zone of the process. Exchanging coke for woodchips will increase the total weight of the reduction agent fed to the furnace for the same amount of fixed carbon, and it will dramatically increase the amount of volatile matter charged to the furnace. The volatiles from the woodchips are much lower in energy content than volatiles from coke and coal, due to the higher content of oxygen in the woodchips. The volatiles in the carbon

materials will go off at increasing temperatures. While CO_2 is emitted at, more or less, a constant rate between 200–700°C, CO and H_2 will leave the carbon materials between 200–800°C and 500–900°C, respectively. While the emissions of these gases from the carbon materials are quite similar for charcoal and coal, the amount of CH_4 will be much higher for coal, around 5 times higher. It will be emitted around 350–800°C for both materials (Smith-Hanssen, 2022). The various gas species were also measured inside the charge for a FeSi and Si furnace and, ignoring the SiO content, the gas, excluding the SiO gas, contained 80–90% CO, which is the product gas, but it also contained close to 10% H_2 , around 5% N_2 , and a couple of percentage of CO_2 , O_2 and CH_4 (Ksiazek *et al.*, 2021).

Carbon – surface burning and losses of fine sized material

In an industrial silicon process, some losses in the carbon materials are observed. To ensure complete combustion of the furnace gas and control the temperature of the gas, it is necessary to allow a large amount of air into the furnace gas outlet. This cooling air may also contribute to some combustion of the reductants. The high gas velocity may result in ‘wind sieving’ or elutriation of carbon fines, especially for carbon materials below 1 mm, which are then burned in the off-gas system (Haugedal, 2025; Johansen *et al.*, 1991). The carbon loss may vary from furnace to furnace, but typical losses are in the order of 5% of the added carbon. The lost carbon will normally burn and add extra energy to the off-gas.

Other minor deviations from an ideal process

In the industrial silicon production process, minor elements of various kinds will normally be recovered in the product. These elements include aluminium, calcium and titanium, which may be reduced from oxides in the same way as silicon. This reduction will use some of the energy during reduction and, hence, appear to increase the specific energy for the silicon reduction. On the other hand, minor elements will also increase the total product-weight over that of pure silicon production.

7.3 Production of ferrosilicon

Iron-silicon alloys, called ferrosilicon, are mainly used for alloying steel and foundry iron. The most frequently used ferrosilicon grades are 75% ferrosilicon and around 50% ferrosilicon. The iron may be added as pure iron (scrap, iron bars etc.) or iron oxide.

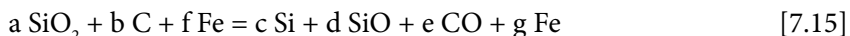
Iron has a major effect on the reduction process as well as the energy balance, as described in Chapter 4. The specific electric energy consumption per ton of alloy is significantly reduced with increasing iron content. The addition of iron oxide will require somewhat more energy than would be true with a metallic iron source. Nevertheless, the specific electric energy consumption per silicon unit is normally lower for ferrosilicon compared to silicon. The principal impact of iron addition to the silicon production process is presented in Table 7.5.

Table 7.5 *The effects of iron addition to a silicon production process.*

No	Effect of iron addition	Comments
1	Higher mass flow per unit silicon.	Enhances the condensation of SiO gas in the upper part of the furnace. This may give higher Si recovery and accompanying lower electric energy consumption.
2	Iron decreases the activity of silicon in the melt.	Reduced silicon activity improves the silicon reduction at a given temperature.
3	Iron oxide reduction is an endothermic process.	The iron oxide reduction consumes energy; this results in higher energy consumption when using iron oxide as an iron source as compared to metallic iron.
4	Iron oxide reduction needs an additional reduction agent.	In ferrosilicon, the available reductants are silicon, CO gas, carbon and volatiles. The latter two are probably most important.

7.4 The material and energy balance for a ferrosilicon process with SiO loss

The chemical reaction for the formation of ferrosilicon with a SiO loss may be presented using metallic iron as an iron source:



A simple mass balance gives the following equations:

$$\text{Silicon balance: } a = c + d \quad [7.16]$$

$$\text{Oxygen balance: } 2a = d + e \quad [7.17]$$

$$\text{Carbon balance: } b = e \quad [7.18]$$

$$\text{Iron balance: } f = g \quad [7.19]$$

When iron oxide is used as an iron source, it is more difficult to calculate the amount of carbon required for the reduction of the iron oxide. In an industrial process, it seems that some of the reduction is performed by the volatiles from the carbon materials. In this calculation, only the last reduction step, from FeO to Fe, requires fixed carbon.

$$a \text{ SiO}_2 + b \text{ C} + f \text{ FeO} = c \text{ Si} + d \text{ SiO} + e \text{ CO} + g \text{ Fe} \quad [7.20]$$

A simple mass balance gives the following equations:

$$\text{Silicon balance: } a = c + d \quad [7.21]$$

$$\text{Oxygen balance: } 2a + f = d + e \quad [7.22]$$

$$\text{Carbon balance: } b = e \quad [7.23]$$

$$\text{Iron balance: } f = g \quad [7.24]$$

Note that no iron oxide loss is assumed.

The energy for the process will be calculated for ferrosilicon containing 75% and 50% silicon. First, a mole-based balance is constructed for these two cases. The molar weight of silicon is 28.09 g/mol, and iron is 55.85 g/mol. The iron balance is shown in Table 7.6.

Table 7.6 *Mass balance for 50% and 75% ferrosilicon*

Iron source	FeSi quality	a	b	c	d	e	f	g
Fe ₂ O ₃	50%	1	1 + 1.701 c	c	1 – c	1 + 1.701 c	0.234 c	0.468 c
Fe ₂ O ₃	75%	1	1 + 1.234 c	c	1 – c	1 + 1.234 c	0.078 c	0.156 c
Fe	50%	1	1 + c	c	1 – c	1 + c	0.468 c	0.468 c
Fe	75%	1	1 + c	c	1 – c	1 + c	0.156 c	0.156 c

For a specific case, a silicon recovery of 90% is chosen, and the result is presented in Table 7.7.

Table 7.7 *Mass balance for 50% and 75% ferrosilicon at 90% silicon yield*

Iron source	FeSi quality	a	b	c	d	e	f	g
Fe ₂ O ₃	50%	1	2.53	0.9	0.1	2.53	0.211	0.42
Fe ₂ O ₃	75%	1	2.11	0.9	0.1	2.11	0.070	0.14
Fe	50%	1	1.90	0.9	0.1	1.90	0.421	0.42
Fe	75%	1	1.90	0.9	0.1	1.90	0.140	0.14

Note the difference in the carbon requirement given by factor b in Table 7.7. The increase in carbon when using iron oxide is approximately 11% and 33% for 75% ferrosilicon and 50% ferrosilicon respectively, compared to the use of metallic iron. Such a difference is not normally observed, and the reason seems to be that both CO and the volatiles take part in the reduction of iron oxide. Carbon in the volatile material will not play the same role as the fixed carbon for silicon reduction, because only a minor part of this carbon participates in the silicon reduction. However, some of the volatiles may reduce the iron oxide. A rule of thumb for 75% ferrosilicon is that volatiles or CO reduce Fe₂O₃ to FeO, and it will only use reaction heat from the upper part of the process. The reduction from FeO to Fe is probably carried out by fixed carbon and will use electric energy from the process. For lower silicon grades, such as 50% ferrosilicon, almost the entire iron reduction process will require fixed carbon and will use electric energy. For FeSi52, it is shown that the difference in energy consumption will be about 16% higher if FeO is reduced with solid carbon, compared to CO gas (Saadieh, 2024). This discussion is very important for the process energy balance because volatile or CO-gases serving as reductants will not provide combustion energy in the off-gas.

7.5 Real life – a silicon and a ferrosilicon furnace

All the information above can be combined to calculate a mass and an energy balance for a real furnace. The calculation will be based on some simple characteristics of the furnace and the carbon materials discussed above. From the calculation a simple energy flow sheet can be drawn for the process.

The 'size' of a furnace is normally determined by the electric power. The power is often measured at the secondary transformers. From the transformer to the tip of the electrodes, electric losses occur due to resistance and inductance. In this calculation, it is important to divide the losses into various groups depending on where the energy will flow. An energy balance for the electric system from the transformers to the process is presented in Table 7.8

Table 7.8 *Electrical losses for a 10 MW silicon furnace*

Electric loss in:	Losses (kW)	Losses (% electric energy input)	Energy to be found as:
Transformers and busbars	400	4	Heat in the cooling water
Smoke hood, charging equipment, etc.	300	3	Heat in cooling water or as steam in a boiler
Electrode resistance	900	9	Partly radiation to the off-gas above the charge level, partly heating of raw materials
Total	1600	16	

The 'useful' electric energy from a 10 MW furnace, delivered to the process, is reduced by 16%. The electricity available for silicon production is hence 8.4 MW. Other losses should be considered. Heat losses from the furnace body are estimated at approximately 5% of the electricity input. The losses presented in Table 7.8 are indicative figures. Exact losses will vary from furnace to furnace due to different designs.

The material balance for the process may be calculated from Table 7.3 simply by multiplying the numbers by $8.4 \text{ MW}/20 \text{ MW} = 0.42$. Once the fixed carbon requirement is established, the choice of carbon source will determine the energy in the process. The carbon reductants can be expressed as their percentage contribution to the total amount of fixed carbon fed to the process.

An example of a fixed carbon distribution could be a charge containing 10% from coke, 70% from coal and 20% from woodchips.

The following tables show the total energy flow in and out of the process. Note the importance of the volatiles in Table 7.9. The table shows that the electric energy is somewhat less than half of the energy into the process.

Table 7.9 *Energy delivered to a 10 MW silicon furnace.*

Energy type	Energy into the process (kW)	Part
Electric energy	10000	45%
Chemical energy fixed carbon	6353	29%
Chemical energy volatiles	5843	26%
Total	22196	100%

Table 7.10 shows the energy output from the process. Note that the energy in the off-gas output is 1.16 times the electric energy input to the process. The figures are indicative. To determine the exact energy distribution for a given design and operating strategy, calculations and/or measurements must be carried out.

Table 7.10 *The energy output from the 10 MW silicon furnace.*

Energy type:	Energy from the process (kW)	Part
Chemical energy product	7160	32%
Heat in product	730	3%
Energy in the off-gas	11353	51%
Cooling water	1822	8%
Radiation and convection	1131	5%
Total	22196	100%

The energy balance is also illustrated in Figure 7.8. These results may be considered typical for a silicon process, but the parameters used in the calculation may not apply to every furnace. To determine the energy balance for a specific furnace, calculations and/or measurements must be carried out, as e.g. Myrhaug (2003), Kamfjord (2010) and Takla (2013) did, to mention a few.

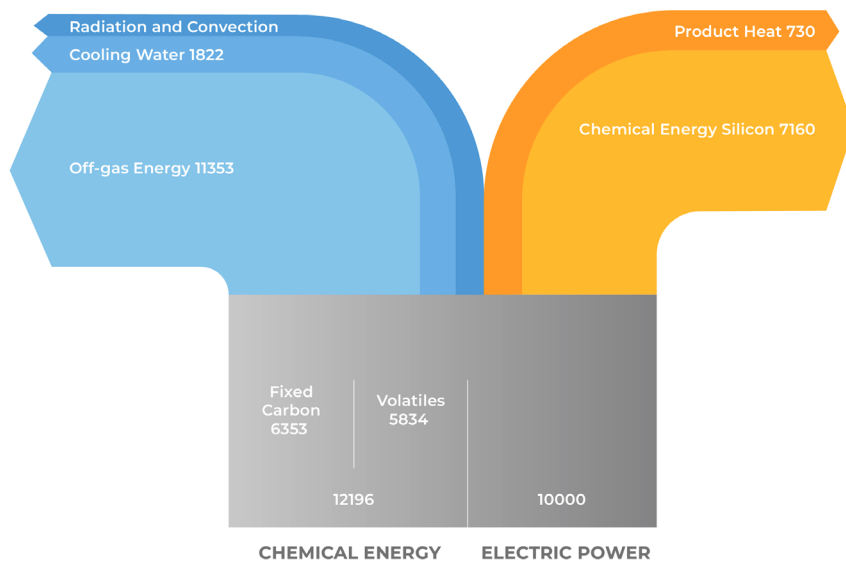


Figure 7.7 showing the energy to and from a 10 MW silicon furnace.

7.6 Energy recovery from the process

Conceivable energy recovery

A disadvantage of the current technology used to produce silicon alloys is the large amount of energy that is not used in the reduction step. As seen in Figure 7.8, only about 32% of the energy consumed is chemical energy in the product. In other words, approximately 68% of the energy is lost as waste heat. Some direct process improvements are conceivable, such as running the process with a high silicon yield, improving the furnace design to achieve lower electric energy loss, or reducing the amount of volatiles fed to the process. Another possibility is to install energy recovery systems. The most readily recoverable energy is in the cooling water. It could be used for various low-temperature purposes, such as fish farming or the heating of buildings.

The largest recoverable energy source is in the off-gas. In larger heat recovery systems, this energy can be used to produce warm water, saturated steam for heating, or superheated steam for electricity production. Today, most Si/FeSi plants in Norway do have energy recovery systems producing electrical energy. This could be done through boilers connected to the furnaces. In

the boilers, the off-gas is cooled down from 600–750°C to 170°C by passing it through a superheater, boiler and economiser heat exchangers. The boiler can produce superheated steam at approximately 460°C and 50 bar pressure. The steam can be fed to a multi-stage reaction turbine, which is linked to a generator. The electric energy produced is typically approximately 30% of the energy in the off-gas. Compared with the production of thermal energy as warm water or steam, the yield is lower when the energy is recovered as electricity.

The potential energy recovery increases with increasing off-gas temperature. It has already been mentioned that a high volume of cooling air is used to control the off-gas temperature. In industrial silicon production, the temperature is in the range from 200°C to 700°C after combustion and mixing with cool air. Normally, there is a limitation for the off-gas temperature to the filters that is around 150°C, to avoid the harmful generation of sulphurous acid.

The off-gas temperature for the theoretical silicon production process was calculated previously in this chapter. The industrial process will differ from this by having more gas components, such as volatiles and water vapour. This will make the temperature increase with increasing air inlet less than that shown in Figure 7.2. On the other hand, volatiles and carbon fines give extra energy when burned. The burning of volatiles and carbon fines will most likely take place after the SiO combustion, but before all the CO gas is burned.

The energy recovery system must be able to adjust to varying conditions at the furnace, both regarding carbon materials, Si-yield and load, to mention some. In Figure 7.9 and Figure 7.10, examples of daily variations can be seen, where the FixC may vary regarding over-coking and under-coking strategies, the amount of volatiles may change based on available raw materials, and the load may change. This will affect the flows out, and the energy in the off-gas changes about 20% from max to min. When the load also changes, the daily variations may be larger.

To increase energy recovery, the most important parameters are, according to Kamfjord (2010), a high furnace load, a larger furnace size and higher off-gas temperatures. As described above, volatiles will also affect the total energy content in the off-gas. Good access to cold cooling water will allow a lower condensator pressure, which also affects energy recovery.

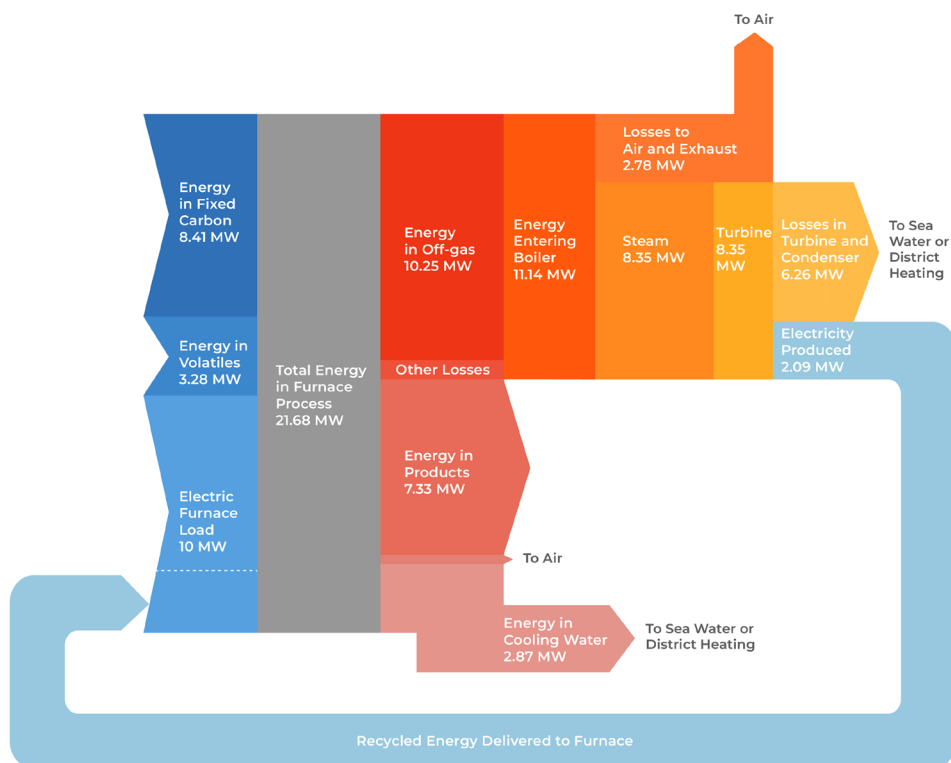


Figure 7.8 shows a Sankey diagram where the energy recovery is shown (Kamford et al., 2010).

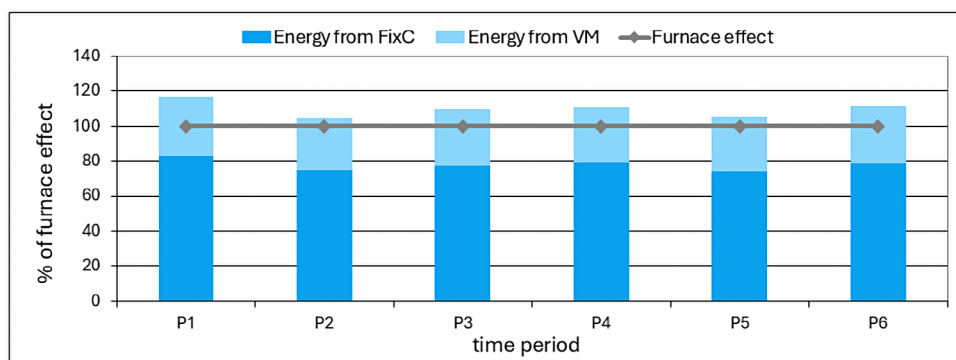


Figure 7.9 Variation of energy into a FeSi furnace given as averages over 8 hours (Kamford et al., 2010).

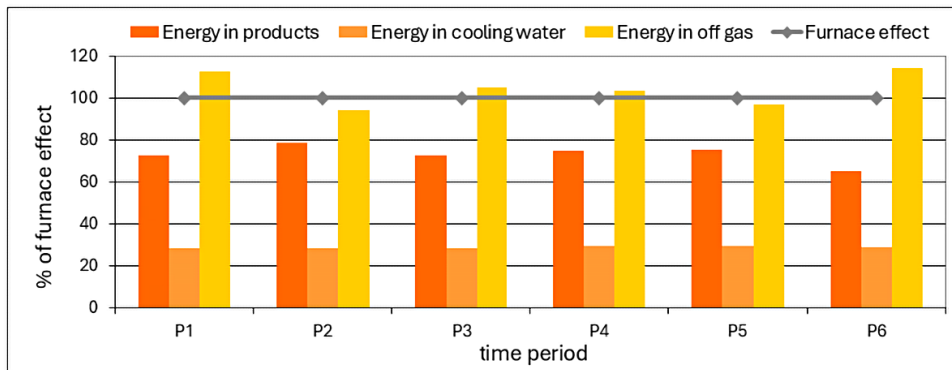


Figure 7.10 Variation of energy from a FeSi furnace given as averages over 8 hours (Kamfjord et al., 2010).

7.7 Exergy analyses

Exergy is the maximum amount of work obtainable when an energy carrier is brought from its initial state to a state of thermodynamic equilibrium with the common substances of the natural environment (by means of reversible processes) (HSC Chemistry). Exergy can also be used to quantify the ‘quality of energy’. Hence, the exergy destruction during a process indicates how much the quality of the energy deteriorates. The quality of energy can be exemplified by 1 kWh of electrical energy having a higher exergy than 1 kWh of hot water. The exergy term also represents how easy it is to recycle energy, or to make electricity out of the energy, hence, the higher the temperature of a gas, solid or liquid, the higher the exergy.

The exergy content of a material flow contains chemical and physical energy, and here we will use the terminology described by HSC Chemistry.

$$E_{ch.} = \sum_k n_k b_k^{ref.} + \Delta G_{f(25^\circ C, 1bar)}^0$$

where n_k is the stoichiometric amount of element k in the species, $b_k^{ref.}$ is the elemental exergy of element k and $\Delta G_{f(25^\circ C, 1bar)}^0$ is the standard formation Gibbs free energy of the species.

$$E_{ph.} = \left(H_i - H_{i(25^\circ\text{C}, 1\text{bar})} \right) - T_{25^\circ\text{C}} \left(S_i - S_{i(25^\circ\text{C}, 1\text{bar})} \right)$$

where H_i is the total enthalpy of the species at the temperature of T, $H_{i(25^\circ\text{C}, 1\text{bar})}$ is the enthalpy of the species in the standard state, S_i is the total entropy of the species at the temperature of T, and $S_{i(25^\circ\text{C}, 1\text{bar})}$ is the entropy of the species in the standard state. Today, one can use easy tools like e.g. HSC Chemistry to calculate the exergy and exergy destruction of processes in the same manner as enthalpy energy (=enthalpy) calculations.

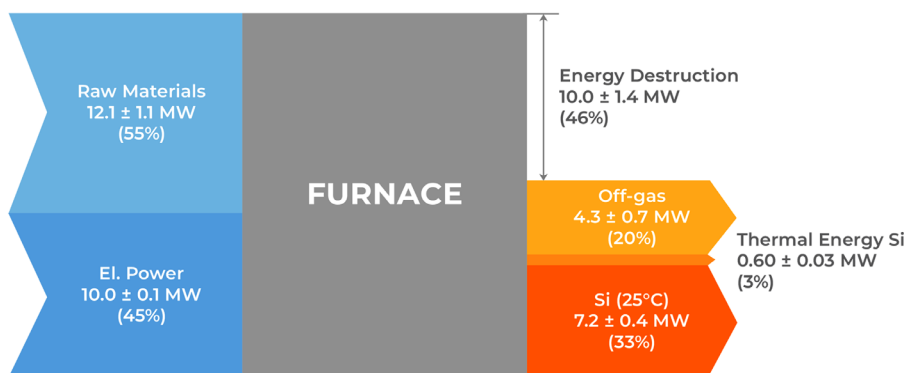


Figure 7.11 A Grassman diagram illustrating the exergy flow for a 45 MW submerged arc furnace operating. The numbers are scaled to a 10 MW furnace. The off-gas temperature is 260°C. (Adapted from Takla *et al.*, 2013).

Takla *et al.* (2013) and Børset (2015) did calculations of the exergy destruction, or the exergy efficiency, for various Si process-cases. Figure 7.11 shows a case investigating the exergy flow in and out of the Si-process. The main exergy flows out of the process are the off-gas and the energy in the product, as also the enthalpy balances show (Figure 7.8, Figure 7.11). For this example, the exergy destruction is 46%, that is with an exergy efficiency of 54%. Both the electric energy and the carbon have high exergy contents, and we see that the ratios between the exergies in raw materials and electrical energy are about the same as the energy in the flows, as seen in Figure 7.11. As we are going from electrical energy and carbon to off-gas with low temperatures, the exergy destruction is quite high. Figure 7.12 shows a number of cases (Takla *et al.*, 2013; Tveit and Kolbeinsen, 2019), with varying degrees of exergy efficiency.

First, one can see that higher Si-yields give higher efficiency, as we are using less energy and fewer carbon materials per ton of silicon, and hence, the total input exergy will be lower. It can also be seen that if one recovers the energy in the off-gas, the exergy efficiency will increase about 20%. If we recover the energy in the off-gas, as well as using the thermal energy from the furnace and the heat in the product, the highest theoretical efficiency will be 75%, and the Best Available Technology (including recovery of energy in off-gas) is expected to be around 70%. Well driven Si-furnaces today, without energy recovery, are expected to be between 30–40% exergy efficiency.

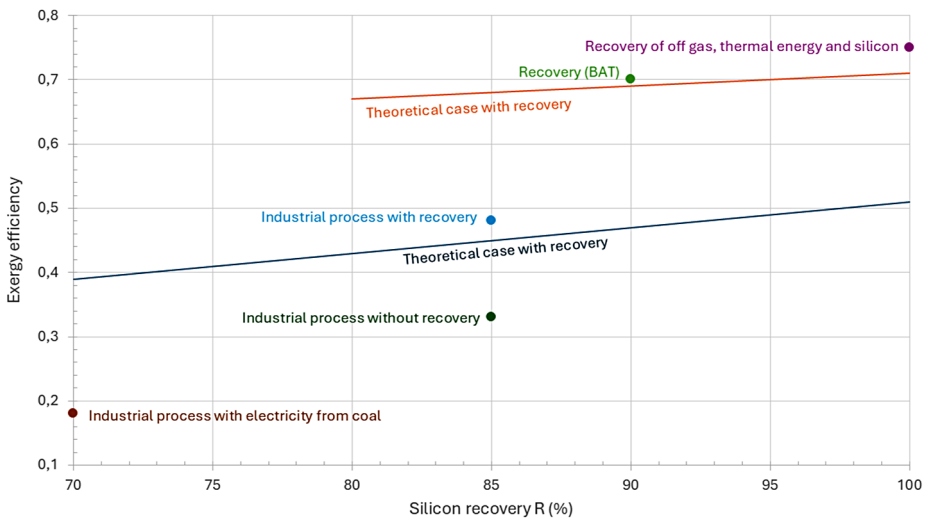


Figure 7.12 Exergetic efficiencies for theoretical and industrial processes. Recovery means power production from thermal energy in the off-gas; for the theoretical process it means utilization of all the thermal exergy in the off-gas at 800°C. One case describing the industrial process also takes into account that the electric power is produced from coal. (Numbers are taken from Takla et al., 2013; Tveit and Kolbeinsen, 2019).

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