«The importance of Silicon to Society»
Professor Leiv Kolbeinsen, Dep. Mat. Sci. & Eng., NTNU

Including a short course in Process Metallurgy
- or rather “Resources, Energy & the Environment”

• Climate change has gone from If to When to Now (World Bank)
• Everyone is entitled to his/her own opinion, but not his/her own facts.
REE -Group
What/Who am I?

**Metal production/-reduction/-oxidation:**
- Liquid Slags and Metals
- Chemical reactions, Mass and energy transfer, Phase relations/ transitions
- Process modeling

«**Environmental metallurgy»:**
- Recycling of metals/slags/dross/energy etc
- Reduction materials
- Waste material prevention
- Resource characterization and optimization

“**Process symbiosis (Industry parks)“** in cooperation with e.g. TSO Sustainability

**Outline**

3 Introductory postulates

Industrial overview

Resources, Energy & Environment
- About «Får-i-kål» & «Kransekake»
- Words on energy
- From Oxide to Metal
- Why CO$_2$-emission?

**CE: Cirkular (Green) Economy**
- Process metallurgy - A role i CE?
- Industrial symbiosis (Industry parks)
Three Postulates:

• The sources of materials obtained from the Earth’s crust, though very large, are finite.
  - This is a fact

• The capacity of the Earth’s ecosystem to cope with the wastes from human production and consumption is finite and by many measures is approaching the limit.
  - This has universal support from scientists and other professionals with deep knowledge of the issue.

• The neo-liberal economic model of unrestrained capitalism as practiced by developed and many developing countries, despite its obvious material benefits over the past decades, has resulted in social and environmental problems on a scale that cannot be solved by market forces alone.
  - This is a hypothesis although increasingly supported by empirical evidence.

Resource Depletion and Waste

Approximately 10% of What Goes ‘in the Pipe’ Comes Out as Goods and Services, the Rest Is Waste

Source: wri.org
3 Introductory postulates

**Industrial overview**

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**CE: Cirkular (Green) Economy**

- Process metallurgy - A role in CE?
- Industrial symbiosis (Industry parks)
<table>
<thead>
<tr>
<th>Position</th>
<th>Plant name when started</th>
<th>Year</th>
<th>Product started</th>
<th>Plant name today</th>
<th>Products today</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Chistiana Spigerverk</td>
<td>1853</td>
<td>Iron</td>
<td>Closed 1989</td>
<td>Elkom 1972 Jernverket 1984</td>
<td></td>
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<td>2</td>
<td>Meraker</td>
<td>1898</td>
<td>CaC2</td>
<td>Closed 2006</td>
<td>Owners: Union Carbie and Elkom</td>
<td></td>
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<td>4</td>
<td>Bjølvefossen Åvik</td>
<td>1905</td>
<td>CaC2 Later FeSi and FeCr</td>
<td>Elkom Bjølvefossen</td>
<td>FeSi and Foundry Products</td>
<td>Elkom from 1986</td>
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<td>5</td>
<td>Odda smelteverk</td>
<td>1906</td>
<td>CaC2</td>
<td>Closed 2002</td>
<td>British Oxygen Company from 1937</td>
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<td></td>
<td>(1924)</td>
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<td>Vennesla</td>
<td>1908</td>
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<td>Hydro Vennesla</td>
<td>Aluminium</td>
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<td>Nikkelraffineringsverk A/S</td>
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<td>9</td>
<td>Arendal SiC</td>
<td>1912</td>
<td>SiC</td>
<td>Saint-Gobain Ceramic Materials</td>
<td>From 2005 only processing of SiC</td>
<td></td>
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<td>10</td>
<td>Eydehavn</td>
<td>1912</td>
<td>Aluminium</td>
<td>Eramet Porsgrunn</td>
<td>FeMn</td>
<td></td>
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<tr>
<td>11</td>
<td>Sultijmela smeltelhytte</td>
<td>1912</td>
<td>Cu</td>
<td>Eramet Porsgrunn</td>
<td>FeMn</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Pea Porsgrunn</td>
<td>1913</td>
<td>FeMn/SiMn</td>
<td>Eramet Porsgrunn</td>
<td>FeMn</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Electric Furnace Products Com</td>
<td>1915</td>
<td>Mn</td>
<td>Eramet Saude</td>
<td>FeMn/SiMn</td>
<td>Union Carbid to 1981 Elkom 1981-99 Eramet from 1999</td>
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<td>14</td>
<td>Tifoss Jernverk AS</td>
<td>1916</td>
<td>Iron</td>
<td>Mn</td>
<td>FeMn, SiMn and Silicon</td>
<td></td>
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<tr>
<td>15</td>
<td>Tyssedal</td>
<td>1916</td>
<td>Aluminium</td>
<td>Ti2r Titanium and iron</td>
<td>Titania slag and iron</td>
<td>Repurposed in 1988 from AI</td>
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<td>16</td>
<td>Elkom Bremanger</td>
<td>1917</td>
<td>Iron</td>
<td>Elkom Bremanger</td>
<td>FeSi, Silgrain</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Det Norske Zinkkompani A/S</td>
<td>1924</td>
<td>Zink</td>
<td>Boliden Odda As</td>
<td>Zn / Al</td>
<td></td>
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<tr>
<td>18</td>
<td>Lilleby smelteverk</td>
<td>1927</td>
<td>FeSi</td>
<td>Closed 2002</td>
<td></td>
<td></td>
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<tr>
<td>19</td>
<td>AS Tafjord Smelteverk</td>
<td>1930</td>
<td>FeSi</td>
<td>Closed 1962</td>
<td></td>
<td></td>
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<td>20</td>
<td>Orkla Metall</td>
<td>1931</td>
<td>Cu and S FeSi from 1964</td>
<td>Elkom Thamshavn</td>
<td>Si + microsilica</td>
<td>Orkla to 1986 - Elkom 1986 -</td>
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<tr>
<td>21</td>
<td>Norsk Jernverk</td>
<td>1946</td>
<td>Iron/Steel</td>
<td>Calsa Armeringsstål, FeSi, Glencore Manganese</td>
<td>Steel FeMn FeSi SiMn</td>
<td>Started 1955 Restructured 1988</td>
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<tr>
<td>22</td>
<td>Årdal</td>
<td>1948</td>
<td>Al</td>
<td>Hydro Aluminium AS Årdal</td>
<td>Al</td>
<td>Hydro Aluminium</td>
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<tr>
<td>23</td>
<td>Sunndal</td>
<td>1954</td>
<td>Al</td>
<td>Sunndal Primary Production</td>
<td>Al</td>
<td>Hydro Aluminium</td>
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<tr>
<td>24</td>
<td>Mosa Mosjøen</td>
<td>1958</td>
<td>Al</td>
<td>Alcoa Mosjøen</td>
<td>Al, carbon</td>
<td>Elkom/Alcoa - Alcoa 2009</td>
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<td>25</td>
<td>Fesil Nord</td>
<td>1960</td>
<td>FeSi</td>
<td>Finnfjord Smelteverk</td>
<td>FeSi</td>
<td>Finnfjord Smelteverk from 1983</td>
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<tr>
<td>26</td>
<td>Holla verk</td>
<td>1962</td>
<td>FeSi</td>
<td>Wacker Chemicals Norway As Holla Metall</td>
<td>Silicon</td>
<td>Fesil sold to Wacker 2010</td>
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<tr>
<td>27</td>
<td>Husnes</td>
<td>1962</td>
<td>Al</td>
<td>Hydro Husnes</td>
<td>Al</td>
<td>Rio tinto / Hydro</td>
</tr>
<tr>
<td>29</td>
<td>Hydro Karmøy</td>
<td>1963</td>
<td>Al</td>
<td>Karmøy Primary Production</td>
<td>Al</td>
<td>Hydro Aluminium</td>
</tr>
<tr>
<td>30</td>
<td>Elkom Salten</td>
<td>1967</td>
<td>FeSi</td>
<td>Elkom Salten</td>
<td>Si FeSi</td>
<td></td>
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<tr>
<td>31</td>
<td>Elkom Lista</td>
<td>1971</td>
<td>Al</td>
<td>Alcoa Lista</td>
<td>Al</td>
<td>Elkom/Alcoa - Alcoa 2009</td>
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<tr>
<td>32</td>
<td>Tifoss Øye</td>
<td>1974</td>
<td>SiMn</td>
<td>Eramet Kvinnesdal</td>
<td>SiMn</td>
<td>Eramet from 2008</td>
</tr>
</tbody>
</table>
Net consumption of electricity in Norway.

- private households and agriculture: 34%
- construction and other services: 21%
- mining and extraction: 3%
- manufacturing (excl. power intensive manufacturing): 7%
- power intensive manufacturing: 26%
- manufacture of pulp, paper and paperboard: 3%

- industrial chemicals: 6%
- iron, steel and ferroalloys: 4%
- non-ferrous metals: 16%
- Al: 64%
- Si and FeSi: 9%
- FeMn and SiMn: 2%
- Titania slag: 3%
- SiC: 1%
- Ni, Co, Cu: 1%
- Zn: 1%

- kWh/kg Al:
  - 1967: 17.5
  - 1993: 15
  - 1998: 14.8
  - 2003: 14.4
  - 2012: 12.5
  - 2014: 12.3
Greenhouse gas emissions by industry in Norway in 2014

- Aluminum
- Silicon products
- Ferromanganese alloys
- Titania slag and iron
- Silicon carbide
- Steel
- Cu, Co, Ni
- Zinc
3 Introductory postulates
Industrial overview (Norway)

**Resources, Energy & Environment**
- About «Får-i-kål» & «Kransekake»
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**CE: Cirkular (Green) Economy**
Process metallurgy - A role in CE?
Industrial symbiosis (Industry parks)
Får-i-kål  (Mutton [Sheep] in Cabbage)

Without Salt and Pepper?
Will I still be fårikål?

Kransekake  (Almond Tower cake)

Using an almond-grinder is cumbersome; food-processor is much easier? (Is that so?)
Food, Energy & Material use

Important elements ~1890:
Food, Energy & Material use
Important elements ~1949:
Food, Energy & Material use
Important elements ~NOW:
Energy Crisis?

The annual global energy consumption, for 2009, was estimated at 16 TW-ys (or 140,160,000,000 KW-hrs) illustrated by the orange sphere on the left-most side.
Energy quality – Energy – Exergy
(what is good use of renewable energy?)

Massflows are usually also Energy flows
- Exergy = f(T, P, a_i) – Quality & amount: Ability to perform work
- => Exergy is what people usually mean when they say «Energy»

It is wise to distinguish between:
- Heat
- Fuel
- Reducing agent
- Electricity
Metal production: Reductants/Energy sources

Stolen from Jean-Pierre Birat (and adapted by me)

- **Carbon**
  - Coke
  - Coal
  - SynGas
  - Natural Gas
  - Blast Furnace (BF)
  - NG reduction

- **Hydrogen**
  - H₂ reduction
  - H₂ from water electrolysis

- **Electrons**
  - Electro steel (EAF)
  - Electrolysis
  - Electricity
  - Decarburization
Copper-like (chalcophile) elements
- Occur primarily in nature as sulfide minerals, and the sulfur in the ore can be utilised as fuel. On the other hand, the sulfur emissions from processing sulfide ores have caused environmental problems by diluting off-gases and increasing the height of smoke stacks are blatant examples of the consequences that might occur when ill formulated environmental regulations are applied.

Strong oxide forming (lithophile) elements
- Silicon, Aluminum, Titanium and Magnesium are generally very abundant in nature, but most of the primary processing methods require large amounts of carbon, either directly as a reducing agent or indirectly for generating electricity for electrolytic processing.

Iron-like (siderophile) elements
- This group also includes nickel, chromium and manganese, the most important additives to steel. The level of production of steel is about 10 times higher than all other metals put together. Iron is also the most recycled (>40%) of the major metals partly due to the fact that the amount of scrap makes its recovery a sizable business.
MeO_x + xR = Me + xRO
[Me = Metal, MeO_x = metal oxide; R = Reducing gas (H_2 or CO) - RO = Oxidized Reducing gas (H_2O or CO_2)]

Figure shows dependance of log(P_{RO}/P_R) on temperature for the equilibrium MeO_x + xR = Me + xRO when R equals H_2.

At first sight these two collection of curves look the same, but:
When solid carbon is present the CO_2 from reduction will react with C and form new CO gas that can reduce metal oxide once more.
Reduction with Hydrogen do not involve a similar function.
Reduce => Refine vs. Refine => Reduce

Figure 8.4: The reduce–refine and refine–reduce sequences for the production of metals.

Silicon is used in a number of processes/applications

- **Ferrosilicon** is used both for removing oxygen from liquid steel and cast iron (de-oxidation), as well as being an alloying element. The end-users are the automotive and construction companies.

- **Silicon is mainly** used for alloying other metals, especially aluminium (about 45 % of global silicon production is for alloying purposes). As for ferrosilicon, the end-users are automotive and construction companies.

- **Silicon is also** used as feedstock for the silicone industry (about 40 %). The end products are typically cosmetics, construction, anti-foam, medical equipment, automotive parts, etc.

- **Silicon is an essential ingredient** in semiconductors and in the solar industry (about 10-15 % and growing). In electronic equipment, the amount of pollution elements must be as low as in the ppb (parts per billion) range. More than 90 % of all electronic components are based on silicon. Another important market for the industry is silicon used in solar cells. Here the pollution level is in the ppm (parts per million) range.
Germany – The Renewable energy leader in total cumulative installations globally and leads by a successful model. In 2014:

<table>
<thead>
<tr>
<th>Country</th>
<th>Cumulative installed solar capacity [GW]</th>
<th>MW/million people</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>38</td>
<td>469</td>
</tr>
<tr>
<td>China</td>
<td>28</td>
<td>20</td>
</tr>
<tr>
<td>Japan</td>
<td>23</td>
<td>181</td>
</tr>
<tr>
<td>India</td>
<td>3</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Germany’s 38 GW accounts for nearly 21 percent of total solar installed capacity in the world (2014). All this makes Germany a key leader in solar power.

There are 2 key elements in Germany’s solar power success that have contributed to substantial rooftop installations:

- Guaranteed grid connection to renewable energy producers and Feed-in-Tariffs (FITs)

By 2013, 23 percent of global residential solar rooftops and 37 percent of global commercial solar rooftop installations took place in Germany*. Governed by the Renewable Energy Sources Act 2000 (Erneuerbare-Energien-Gesetz EEG), renewables including solar enjoy priority grid connection and are supported through Feed-in-Tariffs (FITs) in Germany. This has enabled even the small producers and farmers to connect to the grid and earn revenue by selling solar power.

Silicon in the human body
**ELECTRICAL ENGINEERING OF A SMARTPHONE**

**SCREEN**

- Indium tin oxide is a mixture of indium oxide and tin oxide, used in a transparent film on the screen that conducts electricity. This allows the screen to function as a touch screen.
- The glass used on the majority of smartphones is an aluminosilicate glass, composed of a mix of alumina (Al₂O₃) and silica (SiO₂). This glass also contains potassium ions, which help to strengthen it.
- A variety of Rare Earth Element compounds are used in small quantities to produce the colours in the smartphone’s screen. Some compounds are also used to reduce UV light penetration into the phone.

**BATTERY**

- The majority of phones use lithium ion batteries, which are composed of lithium cobalt oxide as a positive electrode and graphite (Carbon) as the negative electrode. Some batteries use other metals, such as manganese, in place of cobalt. The battery's casing is made of aluminium.

**ELECTRONICS**

- Copper is used for wiring in the phone, whilst copper, gold, and silver are the major metals from which microelectronic components are fashioned. Tantalum is the major component of micro-capacitors.
- Nickel is used in the microphone as well as for other electrical connections. Alloys including the elements praseodymium, gadolinium and neodymium are used in the magnets in the speaker and microphone. Neodymium, terbium and dysprosium are used in the vibration unit.
- Tin & lead are used to solder electronics in the phone. Newer lead-free solders use a mix of tin, copper and silver.
- Magnesium compounds are alloyed to make some phone cases, whilst many are made of plastics. Plastics will also include flame retardant compounds, some of which contain bromine. Nickel can be included to reduce electromagnetic interference.
The Needle in a Haystack
Not easily found – Unpleasant

Trace elements
Dilution - poisoning
Si production and CO\(_2\) emissions

\[
\text{SiO}_2(s) + (1+x)C(s) = x\text{Si} + (1-x)\text{SiO}(g) + (1+x)\text{CO}(g)
\]

<table>
<thead>
<tr>
<th>Electricity source</th>
<th>Total spec. CO(_2) (kg CO(_2)/kg Si)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical C - free</td>
<td>[1.6 (1CO(_2)/Si)] − 3.2 (2 CO =&gt; 2CO(_2)/Si)</td>
</tr>
<tr>
<td>Hydro/Nuclear</td>
<td>4.3</td>
</tr>
<tr>
<td>Gas Power</td>
<td>10.6</td>
</tr>
<tr>
<td>Coal power</td>
<td>17.7</td>
</tr>
</tbody>
</table>
Main steps in the Si-process (Elkem)
What happens when cold CH\(_4\) (g) meets hot SiO (g)?

Condensation chamber, and on the lance:
\[
2 \text{ SiO} \ (g) = \text{SiO}_2 \ (s) + \text{Si} \ (s) \tag{4}
\]
\[
3 \text{ SiO} \ (g) + \text{CO} \ (g) = 2 \text{SiO}_2 \ (s) + \text{SiC} \ (s) \tag{6}
\]

Reaction chamber
\[
\text{SiO} \ (g) + 2 \text{CH}_4 \ (g) = \text{SiC} \ (s) + \text{CO} \ (g) + 4 \text{H}_2 \ (g) \tag{2}
\]
\[
\text{CH}_4 \ (g) = \text{C} \ (s) + 2 \text{H}_2 \ (g) \tag{3}
\]

SiO generator (SiO formation chamber)
\[
2 \text{SiO}_2 \ (s) + \text{SiC} \ (s) = 3 \text{ SiO} \ (g) + \text{CO} \ (g) \tag{5}
\]

Based on a paper by B. Monsen, L. Kolbeinsen, S. Prytz, V. Myrvågnes, and K. Tang at the INFACON conference in Kazakhstan June 2013
Based on a paper by B. Monsen, L. Kolbeinsen, S. Prytz, V. Myrvågnes, and K. Tang at the INFACON conference in Kazakhstan June 2013.
GasFerroSil project

Oxygen in Silica is used to convert CH₄ to “Syn Gas” (H₂ + CO) with Si as bi-product.
Waste Hierarchy

most favoured option

prevention
minimisation
re-use
recycling
energy recovery
landfill

least favoured option
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From “Introduction to Materials” – last century
Today’s aluminium recycling system: cascading use

• The bottom reservoir is formed by automotive secondary castings (mainly engine parts).

• **Today, the cascading system is economically and ecologically meaningful.**
  → It makes use of all the metals (aluminium, alloying elements, other elements)
  → This saves alloying elements for secondary casting

• **In the future, the same system with the same resources may become unsustainable.**
  → Increasing amounts of scrap
  → Limited capacity of engine parts to absorb this scrap
  → Scrap surplus?
Tomorrow’s aluminium recycling system: Closed alloy cycles?

- A closing of alloy cycles would reduce the amount of scrap to be absorbed by automotive secondary castings.
  - Use scrap for alternative applications (sinks)

How could this be achieved in the transport sector?
- Currently, there is a cascading use of about 200 aluminium alloys used in vehicles.
Illustration of the circular economy, Ellen MacArthur Foundation

Where does this company sit within the circular economy?
Elkem: Carbon Neutral Metal Production (CNMP)

Illustration of the circular economy, Ellen MacArthur Foundation

Where does this company sit within the circular economy?
Sustainable business models

Archetypes:
- Maximise material and energy efficiency
- Create value from waste
- Substitute with renewables and natural processes
- Deliver functionality rather than ownership
- Adopt a stewardship role
- Encourage sufficiency

Examples:
- Low carbon manufacturing/solutions
- Circular economy, closed loop
- Reuse, recycle, re-manufacture
- Take back management
- Use excess capacity
- Sharing assets (shared ownership and collaborative consumption)
- Extended producer responsibility

Groupings:
- Technological
- Social
- Organisational

Examples:
- Not for profit
  - Hybrid businesses, Social enterprise (for profit)
  - Alternative ownership: cooperative, mutual, (farmers) collectives
  - Social and biodiversity regeneration initiatives ('net positive')
  - Base of pyramid solutions
  - Collaborative approaches (sourcing, production, lobbying)

- Develop scale up solutions
  - Licensing, Franchising
  - Incubators and Entrepreneur support models
  - Open innovation (platforms)
  - "Patient / slow capital" collaborations
  - “Home based, flexible working"
Energy Value Chain

Exergy

Solar panel for energy export, 20-40% more energy produced than used

Fish farming

Tervirke

Pyrolysis

BTL

BioCarbon

Pyrolysis gas

Diesel

Silicon

Steam

Heat recovery

Recovery > 40% of supplied electric energy

Ethanol

Fermentation

Biogas

Destillation

Pervaporation

Waste heat

Bio-MASS

ORG.

WASTE

Chatalytic Reactor

Hydrogen

Exergy E

Gibbs free energy G

Berndt Wittgens Sintef Materialer og kjemi
**Industrial symbiosis:** cooperative management and exchange of resource flows - particularly materials, water, and energy - through clusters of companies.

Businesses have become increasingly attentive to the price and availability of these resources, the notion of interfirm coordination and management remains underdeveloped and collaborative opportunities are continually overlooked.

This article describes a theory of industrial symbiosis examining the development of what have been called, industrial ecosystems or industrial networks, drawing on a mix of biology and ecology, complex systems-, and organizational theory.

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**Industrial Symbiosis: Main Development Stages**

1) **Sprouting:** Firms begin to exchange resources on a random basis for a variety of reasons. A limited network of interlinked flows takes shape as “kernels” of industrial symbiosis that face a market test and, even when successful, may or may not lead to further exchange activity.

2) **Uncovering:** The realization that some networks have created positive environmental externalities becomes consciously revealed or “uncovered”.

3) **Embeddedness and institutionalization:** In addition to self-organization, further expansion of the network becomes intentionally driven by an institutional entity created at an earlier stage that becomes more deeply established during this stage. As for how long this might last, we have evidence that industrial symbioses can persist over many decades, as is the case of Kalundborg, Denmark, and Kwinana, Australia.

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DOI: 10.1111/j.1530-9290.2011.00450.x
**B&R (Build & Recruit):** Public or private developers create an industrial park or zone and then seek compatible tenants to whom land can be leased or sold. Often an “anchor tenant” is already known; sometimes attracting such a tenant becomes the linchpin for additional development.

**PE-IP (The Planned Eco-Industrial Park):** draws most directly from the build and recruit model. It adds another step, which is a directed effort to identify companies from different industries with a plan to locate them together so that they can share resources across and among themselves. Versions of the PE-IP model have proven to be the least successful of the various approaches so far, particularly in Europe and North America.

In the **SOS (The self-organizing symbiosis)** model an industrial ecosystem emerges from decisions by private agents economically motivated to exchange resources to meet goals such as cost reduction, revenue enhancement, or business expansion.

The **RIP model (Retrofit Industrial Park)**, existing industrial parks are targeted for conversion to eco-industrial parks after build and recruit has occurred. Success is likely to hinge on the degree to which firms in these parks come to accept the norms and values that enable collaboration and interfirm exchange.

The **CEE-IP (Circular Economy Eco-Industrial Park)** model is a new form emerging in China associated with the implementation of the Circular Economy Promotion Law in 2009. So far more than 20 existing sites have been designated as “demonstration eco-industrial parks” as part of the circular economy preparations. Most are retrofits rather than build and recruit models, although many are significant expansions closer in concept to the PE-IP model. Theory suggests that a very positive context for the evolution of symbioses in China now exists.
Resilience is here the system’s ability to absorb disturbances before it changes the variables and processes that control behavior.
Gladstone (Australia) & Kalundborg (Denmark)
The 2052 Forecast: What will happen?

How can metal production contribute?

1. Make sure production does not include any fossil inputs
2. Make sure process is suited for solar power – i.e. direct current and intermittent power
3. Make sure there exist technologies (like CCS) to neutralize greenhouse gas emissions (e.g. CO$_2$ and CH$_4$)
4. Work for a global ban on metals made from fossil fuels – or at least labelling of climate friendly metals

Jorgen Randers Professor Emeritus Climate Strategy BI Norwegian Business School
Metal production: Reductants/Energy sources

Stolen from Jean-Pierre Birat (and adapted by me)

Carbon
- Coke
- Coal
- SynGas
- Natural Gas

Hydrogen
- SynGas
- Natural Gas
- H₂ reduction
- H₂ from water electrolysis

Electrone
- BlastFurnace (BF)
- Blast furnace + plasma
- Electro steel (EAF)
- Electrolysis

Ferro-alloys/silicon & Aluminium

Decarburization
Money is like muck, not good except it be spread.

(Francis Bacon)
It is time to act – decisively!

jorgen.randers@bi.no  www.2052.info
Hi, name is Mingus, Thank you for listening to my «daddy»!
CO₂ fra aluminiumproduksjon
Alternativ C fra CH₄ (Natur- eller Bio-gass)

CO₂ fra silisiumproduksjon
Alternativ C fra CH₄ (Natur- eller Bio-gass)
Elkem: Carbon Neutral Metal Production (CNMP)
Finnfjord Vision
World’s largest ferrosilicon producer without CO₂ emissions
Ambitious
Remote
Type I industrial eco-system (linear material flows)
Type II industrial eco-system (quasi-cyclical).
Type III industrial eco-system (cyclical).