Global Calculator

Technical documentation

Manufacturing sector

Technical documentation (Part 2 Evolution of materials and emissions)

2015
This technical documentation highlights the assumptions used in the manufacturing sector of the global calculator model. Introduction material generic to all sectors should be read prior going through this technical document.

Most of this documentation has been performed to support workshop discussions on the technical choices in the manufacturing sector (in steel, cement, chemicals & across the sector as a whole).

The global calculator aims at supporting the debate. You are more than welcome to share feedback on the calculator and on this documentation. We aim at continuously refining this analysis with your feedbacks. The expert feedback is incorporated in the analysis through various steps:

1. It is flagged as feedback to include in the analysis
2. The analysis documents are refined accordingly
3. The model is updated and the model results are shown in the presentation

The dates of the figures used in the model are written Most of the figures in this document date from July 2014. Please note that some minor modifications have been placed in the model since July 2014. In case of differences between the presentation and the model, the model has the most recent estimates.

All this documentation is open source (1)

NOTE: (1) The Global Calculator spreadsheet and supporting documentation is made available under (and subject to the terms of) the Open Government Licence (www.nationalarchives.gov.uk/doc/open-government-licence/version/2/). The web tool is published under (and subject to the terms of) the Creative Commons Licence (attribution, non-commercial, see: http://creativecommons.org/licenses/by-nc/4.0/legalcode).

As set out in those licences, DECC, IEA and the Climate-KIC consortium provide no express or implied warranties concerning the tool and its contents and, accordingly, those parties accept no liability arising from use of the tool or its contents.
Several slides in this technical documentation document are tagged to reflect the stakeholder consultations.

Legend:

- **Key slide**
- **Key feedback asked**
- **Model input**
- **Consultation feedback still to take into account**
- **Figures of July 2014**

Date of the latest update to the figures in the presentation.
2050 evolution of materials and emissions

Materials demand evolution

- Cross sector demand
- Cross sector material switch
- Steel
- Chemicals
- Aluminium
- Cement
- Paper & Timber

Reduction potential on the manufacturing processes

- Resulting emissions
- Discussion on ambition levels across sectors
- Discussion on CCS
- Steel
- Chemicals
- Aluminium
- Cement
- Paper, Timber & Other
2050 evolution of materials and emissions

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Reduction potential on the manufacturing processes

- Resulting emissions
- Discussion on ambition levels across sectors
- Discussion on CCS
- Steel
- Chemicals
- Aluminium
- Cement
- Paper, Timber & Other
REMINDER: In the model, material demand is driven by product demand

**Steel demand evolution**
(Mtons, before design & switch)

- Cars & light truck
- Cars & light truck EV
- Trucks
- Ships
- Rail
- Residential Buildings
- Other Buildings
- Infrastructure
- Mechanical equipments
- Appliance
- Metal goods
- Consumer packaging
- Windmills
- PV panels
- Electrical Equipment
- Pipes
- Other Steel

• Product demand determines material demand
• How should product demand be determined?

SOURCE: Global Calculator model
REMINDER: Most product demand is defined by sector activity, Some products are driven by the “Product demand” lever,

### Key drivers of demand to be challenged

<table>
<thead>
<tr>
<th>Group</th>
<th>Products</th>
<th>Model Technologies (grouped)</th>
<th>Demand driven by</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>Car &amp; Light trucks</td>
<td>Bike, Cars, Motorbike</td>
<td>By transport sector</td>
<td>Recharge</td>
</tr>
<tr>
<td></td>
<td>Trucks</td>
<td>Trucks, Bus</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rail</td>
<td>Trains</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Airplanes</td>
<td>Planes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trucks &amp; ships</td>
<td>Trucks, Ships</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Roads</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batteries</td>
<td>Electric vehicles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buildings</td>
<td>Buildings</td>
<td>Residential/Non-residential</td>
<td>By buildings sector</td>
<td>Recharge</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Bridges, Roads, Airports</td>
<td></td>
<td>By transport sector</td>
<td>to avoid iteration loop and have it defined in one place</td>
</tr>
<tr>
<td>Mechanical equipment’s</td>
<td>Cooker, HVAC</td>
<td></td>
<td>By Buildings sector</td>
<td>Recharge</td>
</tr>
<tr>
<td>Appliances</td>
<td>Various appliances, stoves, lighting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumer goods</td>
<td>Paper</td>
<td>Print, graphic</td>
<td>By “Product demand “ lever</td>
<td>Recharge</td>
</tr>
<tr>
<td></td>
<td>Metal goods</td>
<td>Consumer products</td>
<td>By “Product demand “ lever</td>
<td>Recharge</td>
</tr>
<tr>
<td></td>
<td>Consumer packaging</td>
<td>Consumer packaging</td>
<td>By “Product demand “ lever</td>
<td>Recharge</td>
</tr>
<tr>
<td>Fertilizers</td>
<td>Ammonia production</td>
<td></td>
<td>By Population</td>
<td>Land &amp; food sector in v2</td>
</tr>
<tr>
<td>Energy/Electricity</td>
<td>Wind</td>
<td>Onshore, offshore</td>
<td>By energy sector</td>
<td>Recharge</td>
</tr>
<tr>
<td></td>
<td>PV</td>
<td>Solar PV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrical Equipments</td>
<td>Transformers</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrical cables</td>
<td>Transmission lines</td>
<td>Skipped</td>
<td>to avoid iteration loop</td>
</tr>
<tr>
<td></td>
<td>Pipes</td>
<td></td>
<td></td>
<td>Not modelled in v1</td>
</tr>
<tr>
<td></td>
<td>Infrastructure (1)</td>
<td>Energy Plants&amp; network</td>
<td>By transport sector</td>
<td>to avoid iteration loop and have it defined in one place</td>
</tr>
<tr>
<td>Industry</td>
<td>Plants of each kind of material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper</td>
<td>Paper</td>
<td></td>
<td>By “Product demand “ lever</td>
<td>Recharge</td>
</tr>
</tbody>
</table>

NOTE: (1) Infrastructure is present in three sectors: Energy, Industry and Transport. The allocation is as follows x.y.z. It’s demand evolution is currently following the transport demand only.
The lever choices in the other sector generate various product evolutions

<table>
<thead>
<tr>
<th>Group</th>
<th>Product</th>
<th>2011 demand (units)</th>
<th>2050 demand per ambition(1) (% evolution vs 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>Cars &amp; light truck</td>
<td>111.3 Million units</td>
<td>Ambition 1: 300%</td>
</tr>
<tr>
<td></td>
<td>Cars &amp; light truck EV</td>
<td>1.5 Million units</td>
<td>Ambition 2: 439%</td>
</tr>
<tr>
<td></td>
<td>Trucks</td>
<td>5.7 Million units</td>
<td>Ambition 3: 184%</td>
</tr>
<tr>
<td></td>
<td>Ships</td>
<td>1 K units</td>
<td>Ambition 4: 101%</td>
</tr>
<tr>
<td></td>
<td>Rail</td>
<td>5 K units</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Airplanes</td>
<td>35 K units</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Batteries</td>
<td>/ Million units</td>
<td></td>
</tr>
<tr>
<td>Buildings</td>
<td>Residential Buildings</td>
<td>3932 Million m2</td>
<td>Ambition 1: 141%</td>
</tr>
<tr>
<td></td>
<td>Other Buildings</td>
<td>830 Million m2</td>
<td>Ambition 2: 230%</td>
</tr>
<tr>
<td></td>
<td>Infrastructure</td>
<td>1750 Million m2</td>
<td>Ambition 3: 307%</td>
</tr>
<tr>
<td></td>
<td>Mechanical equipment</td>
<td>160 Million tons</td>
<td>Ambition 4: 219%</td>
</tr>
<tr>
<td></td>
<td>Appliance</td>
<td>43 Million tons</td>
<td></td>
</tr>
<tr>
<td>Consumer goods</td>
<td>Print &amp; Graphic Paper</td>
<td>253 Million tons</td>
<td>Ambition 1: 152%</td>
</tr>
<tr>
<td></td>
<td>Metal goods</td>
<td>257 Million tons</td>
<td>Ambition 2: 165%</td>
</tr>
<tr>
<td></td>
<td>Consumer packaging</td>
<td>530 Million tons</td>
<td>Ambition 3: 152%</td>
</tr>
<tr>
<td>Food</td>
<td>Fertilizer</td>
<td>164 Million tons</td>
<td>Ambition 4: 169%</td>
</tr>
<tr>
<td>Energy</td>
<td>Windmills</td>
<td>17600 Units</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PV panels</td>
<td>160 Million m2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrical Equipment</td>
<td>61 Million tons</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrical cables</td>
<td>24 Million km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pipes</td>
<td>100 000 km</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>Other</td>
<td>0.0 Million tons</td>
<td></td>
</tr>
</tbody>
</table>

NOTE (1) Population follows the average UN projection in all ambitions.
The lever choices in the other sector generate various product evolutions

<table>
<thead>
<tr>
<th>Group</th>
<th>Product</th>
<th>2011 lifetime (years)</th>
<th>Lifetime per ambition (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>Cars &amp; light truck</td>
<td>12,2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cars &amp; light truck EV</td>
<td>12,4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trucks</td>
<td>12,4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ships</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rail</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Airplanes</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Batteries</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>Buildings</td>
<td>Residential Buildings</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other Buildings</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Infrastructure</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical equipment</td>
<td>21,9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Appliance</td>
<td>11,9</td>
<td></td>
</tr>
<tr>
<td>Consumer goods</td>
<td>Print &amp; Graphic Paper</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Metal goods</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Consumer packaging</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>Food</td>
<td>Fertilizer</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>Windmills</td>
<td>24,1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PV panels</td>
<td>20,0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrical Equipment</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrical cables</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pipes</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>Other</td>
<td>/</td>
<td></td>
</tr>
</tbody>
</table>

NOTE (1) Population follows the average UN projection in all ambitions
Annual Total production per ambition level\(^{(1)}\), by product

(M tons)

Trajectories\(^{(1)}\) in 2050

**NOTE:**  (1) The population follows the average UN projection in all four trajectories

**SOURCE:** IEA ETP 2012, Global calculator model
**Total**

Materials demand growth in trajectories 1, 2, 3 & 4 (1)

---

**Annual Total production per ambition level**, by product
(M tons)

<table>
<thead>
<tr>
<th>Trajectories (1) in 2050</th>
<th>2011</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8,403</td>
<td>749</td>
<td>1,464</td>
<td>2,679</td>
<td>9,751</td>
</tr>
<tr>
<td>2</td>
<td>3,635</td>
<td>611</td>
<td>1,464</td>
<td>5,696</td>
<td>9,751</td>
</tr>
<tr>
<td>3</td>
<td>1,518</td>
<td>809</td>
<td>1,464</td>
<td>1,098</td>
<td>9,751</td>
</tr>
<tr>
<td>4</td>
<td>1,000</td>
<td>809</td>
<td>2,399</td>
<td>1,851</td>
<td>9,751</td>
</tr>
</tbody>
</table>

- **Iron & steel**
- **Chemicals**
- **Aluminium**
- **Cement**
- **Paper**
- **Timber**
- **Other industries**

---

**NOTE:** (1) The population follows the average UN projection in all four trajectories

SOURCE: IEA ETP 2012, Global calculator model
## Total Materials demand growth in trajectories 1, 2, 3 & 4 (1)

### Annual Total production per ambition level (1), by product (M tons)

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>2011</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8,403</td>
<td>8,708</td>
<td>13,593</td>
<td>9,846</td>
<td>7,401</td>
<td>1,659</td>
<td>921</td>
</tr>
<tr>
<td>2</td>
<td>1,518</td>
<td>1,464</td>
<td>2,612</td>
<td>2,112</td>
<td>1,659</td>
<td>1,855</td>
<td>171</td>
</tr>
<tr>
<td>3</td>
<td>749</td>
<td>1,464</td>
<td>5,400</td>
<td>3,129</td>
<td>1,855</td>
<td>1,299</td>
<td>536</td>
</tr>
<tr>
<td>4</td>
<td>611</td>
<td>2,399</td>
<td>197</td>
<td>1,294</td>
<td>1,299</td>
<td>960</td>
<td>921</td>
</tr>
</tbody>
</table>

### Trajectories (1) in 2050

1. **Iron & steel**: +124%
2. **Aluminium**: +62%
3. **Cement**: +17%
4. **Timber**: -12%
5. **Other industries**

### NOTE:
(1) The population follows the average UN projection in all four trajectories

### SOURCE:
IEA ETP 2012, Global calculator model

Figures of July 2014
Total
Materials demand growth in trajectories 1, 2, 3 & 4 (1)

Annual Total production per ambition level(1), by product
(M tons)

<table>
<thead>
<tr>
<th>Product</th>
<th>Trajectory</th>
<th>2011</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel: Oxygen</td>
<td></td>
<td>8,405</td>
<td>18,714</td>
<td>13,393</td>
<td>9,590</td>
<td>7,106</td>
</tr>
<tr>
<td>Steel: Hisarna</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel: Electric</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel: Electric DRI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemicals: HVC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemicals: Ammonia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemicals: Methanol</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemicals: Others</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium: Primary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium: Secondary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper: Virgin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper: Recycled</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper: Recycled</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper: Recycled</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timber</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other industries</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Trajectories(1) in 2050

NOTE: (1) The population follows the average UN projection in all four trajectories
SOURCE: IEA ETP 2012, Global calculator model
Total industry
Materials demand growth with ambition 2 \(^{(1)}\)

Production evolution per industry with an ambition 2, (Mton)

NOTE: \(^{(1)}\) The population follows the average UN projection in all four trajectories
SOURCE: IEA ETP 2012, Global calculator model
2050 evolution of materials and emissions

Materials demand evolution
- Cross sector demand
- Cross sector material switch
  - Steel
  - Chemicals
  - Aluminium
  - Cement
  - Paper & Timber

Reduction potential on the manufacturing processes
- Resulting emissions
- Discussion on ambition levels across sectors
- Discussion on CCS
- Steel
- Chemicals
- Aluminium
- Cement
- Paper, Timber & Other
Each material has a different set of properties

**Embodied Energy**  
(MJ/Kg)

<table>
<thead>
<tr>
<th>Material</th>
<th>Embodied Energy (MJ/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>25</td>
</tr>
<tr>
<td>HDPE</td>
<td>84</td>
</tr>
<tr>
<td>Carbon Fibers</td>
<td>5</td>
</tr>
<tr>
<td>Aluminium</td>
<td>155</td>
</tr>
<tr>
<td>Cement</td>
<td>10</td>
</tr>
<tr>
<td>Concrete</td>
<td>1</td>
</tr>
<tr>
<td>Timber</td>
<td>17</td>
</tr>
</tbody>
</table>

**Density**  
(Kg/m³)

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7,800</td>
</tr>
<tr>
<td>PVC</td>
<td>1,380</td>
</tr>
<tr>
<td>Carbon Fibers</td>
<td>2,700</td>
</tr>
<tr>
<td>Aluminium</td>
<td>1,860</td>
</tr>
<tr>
<td>Cement</td>
<td>1,050</td>
</tr>
<tr>
<td>Concrete</td>
<td>650</td>
</tr>
<tr>
<td>Timber</td>
<td>650</td>
</tr>
</tbody>
</table>

- Embodied energy reflects the amount of energy needed to produce a kg of the material in the model before any efficiency lever is applied.
- Density reflects xxxx.

SOURCE: Bath construction database
The specific Young modulus indicates how much of a material is required to replace another.

Specific Young modulus (Young modulus in Gpa, divided by density)

### Rationale
- We use these figures to compute how much material is required to replace another (e.g., ~2x the weight of timber to replace steel).
- This is a high level approximation and the conversion factor should differ for each pair of products.
- Product lives are assumed to be similar.

NOTE: (1) Tweaked to 20% more than steel, to represent the fact 20% less mass is typically required in transport applications
(2) Assuming 8% cement per ton concrete
(3) Assuming Pine, then removing 40% to account to material discontinuity safety factor

SOURCE: Wikipedia Specific modulus
## Material switches in Transport

<table>
<thead>
<tr>
<th>Groups</th>
<th>Products</th>
<th>Units</th>
<th>Composition per unit (tons, (vs 2011))</th>
<th>Ambition 1</th>
<th>Ambition 4</th>
</tr>
</thead>
</table>
| Transport | Cars & light truck | units | Steel: 1,150 ton Alu: 0,15 ton HVC: 0,1 ton Methane: 0,02 ton Other chem: 0,07 ton | idem | Replace  
• 20% steel by aluminium  
• 20% steel by carbon fibres |
| | Trucks | units | Steel: 3,030 ton Alu: 1 ton HVC: 0,3 ton Methanol:0,06ton Other chem: 0,2ton | idem | Replace  
• 20% steel by aluminium  
• 20% steel by carbon fibres |
| | Ships | units | Steel: 0,462 ton | idem | Idem |
| | Rail | units | Steel: 6,875 ton | idem | Idem |
| | Airplanes | units | Alu: 63 ton | idem | Replace  
• 50% alu by carbon fiber (HVC) |
# Material switches in Buildings

<table>
<thead>
<tr>
<th>Groups</th>
<th>Products</th>
<th>Units</th>
<th>Composition per unit (tons, (vs 2011))</th>
<th>Ambition 1</th>
<th>Ambition 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Buildings</strong></td>
<td><strong>Buildings</strong></td>
<td>m² (ground surface)</td>
<td>Steel: 0,202 ton Alu: 0,008 ton HVC: 0,02 ton Methanol: 0,004 ton Other chem: 0,004 ton Cement: 0,560 ton Bricks: not modelled Timber: 0,22 ton</td>
<td>idem</td>
<td>Replace</td>
</tr>
<tr>
<td>(residential &amp; others)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• 20% steel by timber • 20% concrete by timber • 5% concrete by insulation materials (HVC)</td>
</tr>
<tr>
<td><strong>Infrastructure</strong></td>
<td>m² (ground surface)</td>
<td>Steel: 0,187 ton Alu: 0,001 ton Cement: 0,450 ton</td>
<td>idem</td>
<td>Replace</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• 5% concrete by insulation materials (HVC)</td>
</tr>
<tr>
<td><strong>Mechanical equipment</strong></td>
<td>tons</td>
<td>Steel: 0,750 ton Alu: 0,013 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td><strong>Appliance</strong></td>
<td>Million tons</td>
<td>Steel: 0,17 ton Alu: 0,02 ton HVC: 0,43 ton Methanol: 0,08 ton Other chem: 0,28ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
</tbody>
</table>
### Material switches in Consumer goods and Energy

#### Groups

<table>
<thead>
<tr>
<th>Products</th>
<th>Units</th>
<th>Composition per unit (tons, (vs 2011))</th>
<th>2011</th>
<th>Ambition 1</th>
<th>Ambition 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Consumer goods</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Print &amp; Graphic Paper</td>
<td>Million tons</td>
<td>Paper: 1 ton</td>
<td>Steel: 0,750 ton</td>
<td>idem</td>
<td>idem</td>
</tr>
<tr>
<td>Metal goods</td>
<td>Million tons</td>
<td>Steel: 0,03 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td>Consumer packaging</td>
<td>Million tons</td>
<td>Steel: 0,021 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steel: 0,023 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HVC: 0,240 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Methanol: 0,04 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paper: 0,516 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td>Fertilizer</td>
<td>tons</td>
<td>Ammonia: 1 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windmills</td>
<td>2MW Units</td>
<td>Steel: 350 tons</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HVC: 30 tons</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td>PV panels</td>
<td>m2</td>
<td>Steel: 2 kg</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alu: 2 kg</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HVC: 5 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td>Electrical equipment</td>
<td>tons</td>
<td>Steel: 0,750 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alu: 0,03 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td>Electrical cables</td>
<td>Km</td>
<td>Alu: 0,3 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td>Pipes</td>
<td>meter</td>
<td>Steel: 0,4 ton</td>
<td>idem</td>
<td>idem</td>
<td></td>
</tr>
</tbody>
</table>

- In packaging, both a tendency to more (e-shipping) and to less (more lightweight, tailored to needs) packaging
- Check expectations with EU packaging federation
Open questions

Discussion topics on material switch

<table>
<thead>
<tr>
<th>Trends</th>
<th>Impact of urbanisation on the proportion of Steel/Cement in buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intellectual capital</td>
<td>Which working groups compare the applicability of materials</td>
</tr>
<tr>
<td></td>
<td>Which dimensions should be taken into account</td>
</tr>
<tr>
<td></td>
<td>Vedh has a working group</td>
</tr>
<tr>
<td></td>
<td>Others ?</td>
</tr>
<tr>
<td>Other dimensions to take into account</td>
<td>All products could keep similar lifetimes</td>
</tr>
<tr>
<td></td>
<td>Timber is less uniform, so a safety margin needs to be included</td>
</tr>
<tr>
<td></td>
<td>(current assumption of +40% requirements)</td>
</tr>
<tr>
<td></td>
<td>Fiber glass cannot be recycled and are harder to repair</td>
</tr>
<tr>
<td>Costs</td>
<td>How to you suggest to account of the costs associated with each material? Use the embedded energy of each material?</td>
</tr>
<tr>
<td>Magnitude orders</td>
<td>Overall substitution rate through the above is limited, even in level 4:</td>
</tr>
<tr>
<td></td>
<td>-11% steel, -1% aluminium, -16% cement</td>
</tr>
</tbody>
</table>
2050 evolution of materials and emissions

Materials demand evolution
  • Cross sector demand
  • Cross sector material switch

  • Steel
    • Chemicals
    • Aluminium
    • Cement
    • Paper & Timber

Reduction potential on the manufacturing processes
  • Resulting emissions
  • Discussion on ambition levels across sectors
  • Discussion on CCS
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper, Timber & Other
As income /person increases, steel demand increases, an upper boundary is experienced in some countries

Evolution of steel per capita consumption as function of GDP per capita
(ton/person, 1990 International $/person)\(^{(1)}\)

Steel Demand can be correlated to national incomes, up to $20-000/person, but then the increase declines, when demand for new products, buildings & infrastructure has been satisfied.

Steel stocks appear to saturate between 8 & 12 tons /person\(^{(2)}\)\(^{(1)}\).

This indicates we will reduce our consumption to a level were we will consume what needs to be replaced.

 SOURCES: (1) With both eyes open, Copyright 2012 UIT Cambridge Ltd.
 (2) NTNU & Cambridge University (2014 04 10 International Materials Education Symposium)
Rationale for assessing future steel production

| Population evolution          | 7 billion people in 2010\(^{(3)}\)  
|                             | 8-10 billion people in 2050 \(^{(3)}\) |
| Demand per capita evolution  | Per capita  
|                             | • 201 kg/capita in 2010  
|                             | • 225-270 kg/capita in 2050 \(^{(4)}\)  
|                             | • 270-319 kg/capita in 2050 \(^{(1)}\) |
| Regional changes             | We expect continuing growth in the steel production, driven by developing areas\(^{(3)}\), where steel will be vital in raising the welfare of developing societies. In these regions, more than 60% of steel consumption will be used to create new infrastructure\(^{(2)}\) |
| Market segment changes       | • Increasing share of manufactured steel goods vs buildings & infrastructure  
|                             | (building and infrastructure construction slows in China into 2050, and China's demand for steel containing goods such as cars & domestic appliances increases) \(^{(4)}\) |
| Total range                  | • Based on the above indicative range between 1608 to 3190 M tons in 2050  
|                             | • IEA ETP 2012 has 2438 to 2943 M tons in 2050 |
## Rationale for expected 2050 Iron & steel demand (2/2)

### Technologies & Products

<table>
<thead>
<tr>
<th>Building Residential</th>
<th>Evolution driven by</th>
<th>Assumptions (if by product demand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings Residential</td>
<td>Building model</td>
<td>/</td>
</tr>
<tr>
<td>Buildings Others</td>
<td>Building model</td>
<td>/</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Transport demand (pass. &amp; freight)</td>
<td>linked to transport demand</td>
</tr>
<tr>
<td>Electrical equipment</td>
<td>Product demand lever</td>
<td>100-175% evolution by 2050</td>
</tr>
<tr>
<td>Mechanic equipment</td>
<td>Building model</td>
<td>/</td>
</tr>
<tr>
<td>Consumer packaging</td>
<td>Product demand lever</td>
<td>80-110% evolution by 2050</td>
</tr>
<tr>
<td>Appliance</td>
<td>Building model</td>
<td>/</td>
</tr>
<tr>
<td>Metal goods</td>
<td>Product demand lever</td>
<td>80-120% evolution by 2050</td>
</tr>
<tr>
<td>Cars &amp; light truck</td>
<td>Transport model</td>
<td>/</td>
</tr>
<tr>
<td>Trucks</td>
<td>Transport model</td>
<td>/</td>
</tr>
<tr>
<td>Ships</td>
<td>Transport model</td>
<td>/</td>
</tr>
<tr>
<td>Rail</td>
<td>Transport model</td>
<td>/</td>
</tr>
<tr>
<td>Windmills</td>
<td>Supply model</td>
<td>/</td>
</tr>
<tr>
<td>PV panels</td>
<td>Supply model</td>
<td>/</td>
</tr>
<tr>
<td>CCS + oil pipes</td>
<td>Not linked in this version of the model</td>
<td>/</td>
</tr>
<tr>
<td>Other Steel</td>
<td>Product demand lever</td>
<td>100%-175% evolution by 2050</td>
</tr>
</tbody>
</table>

**SOURCE:** (1) Global Calculator team assumptions
The IEA ETP 2012 suggests an increase in Iron & Steel production in all scenarios in most regions.

Production evolution per scenario per region for Steel (Mton)

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Steel (Crude)</th>
<th>Scrap Consumption (part of Total Steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2009</td>
<td>2050 Low</td>
</tr>
<tr>
<td></td>
<td>1,232</td>
<td>2,438</td>
</tr>
</tbody>
</table>

**SOURCE:** ETP 2012, IEA
By 2050, the world population is expected by the UN to grow by ~20 to ~55%.

World population (billions)

2010-2050 growth (%)

- High variant: +57%
- Medium variant: +38%
- Low variant: +21%

SOURCE: http://esa.un.org/unpd/wpp/unpp/panel_population.htm 2012 revision
Global calculator growth forecasts
Production according to trajectories 1, 2, 3 & 4 (based on sectors demand, before design, switch & recycling)

Steel production per year per ambition level\(^{(1)}\)
(M tons)

<table>
<thead>
<tr>
<th>Year</th>
<th>Trajectory 1</th>
<th>Trajectory 2</th>
<th>Trajectory 3</th>
<th>Trajectory 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>1,500</td>
<td>2,000</td>
<td>2,500</td>
<td>3,000</td>
</tr>
<tr>
<td>2015</td>
<td>1,875</td>
<td>2,400</td>
<td>2,900</td>
<td>3,400</td>
</tr>
<tr>
<td>2020</td>
<td>2,250</td>
<td>2,750</td>
<td>3,250</td>
<td>3,750</td>
</tr>
<tr>
<td>2025</td>
<td>2,625</td>
<td>3,125</td>
<td>3,625</td>
<td>4,125</td>
</tr>
<tr>
<td>2030</td>
<td>3,000</td>
<td>3,500</td>
<td>4,000</td>
<td>4,500</td>
</tr>
<tr>
<td>2035</td>
<td>3,375</td>
<td>3,875</td>
<td>4,375</td>
<td>4,875</td>
</tr>
<tr>
<td>2040</td>
<td>3,750</td>
<td>4,250</td>
<td>4,750</td>
<td>5,250</td>
</tr>
<tr>
<td>2045</td>
<td>4,125</td>
<td>4,625</td>
<td>5,125</td>
<td>5,625</td>
</tr>
<tr>
<td>2050</td>
<td>4,500</td>
<td>5,000</td>
<td>5,500</td>
<td>6,000</td>
</tr>
</tbody>
</table>

Delta 10-50%

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+124%</td>
</tr>
<tr>
<td>2</td>
<td>+96%</td>
</tr>
<tr>
<td>3</td>
<td>+83%</td>
</tr>
<tr>
<td>4</td>
<td>+73%</td>
</tr>
</tbody>
</table>

Implied demand per person

<table>
<thead>
<tr>
<th>Year</th>
<th>Trajectory 1</th>
<th>Trajectory 2</th>
<th>Trajectory 3</th>
<th>Trajectory 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>355 kg</td>
<td>316 kg</td>
<td>291 kg</td>
<td>275 kg</td>
</tr>
<tr>
<td>2015</td>
<td>387 kg</td>
<td>348 kg</td>
<td>323 kg</td>
<td>304 kg</td>
</tr>
<tr>
<td>2020</td>
<td>419 kg</td>
<td>381 kg</td>
<td>355 kg</td>
<td>336 kg</td>
</tr>
<tr>
<td>2025</td>
<td>451 kg</td>
<td>413 kg</td>
<td>387 kg</td>
<td>368 kg</td>
</tr>
<tr>
<td>2030</td>
<td>483 kg</td>
<td>445 kg</td>
<td>419 kg</td>
<td>399 kg</td>
</tr>
<tr>
<td>2035</td>
<td>515 kg</td>
<td>477 kg</td>
<td>451 kg</td>
<td>431 kg</td>
</tr>
<tr>
<td>2040</td>
<td>547 kg</td>
<td>509 kg</td>
<td>483 kg</td>
<td>463 kg</td>
</tr>
<tr>
<td>2045</td>
<td>579 kg</td>
<td>541 kg</td>
<td>515 kg</td>
<td>495 kg</td>
</tr>
<tr>
<td>2050</td>
<td>611 kg</td>
<td>573 kg</td>
<td>547 kg</td>
<td>527 kg</td>
</tr>
</tbody>
</table>

NOTE: (1) The population follows the average UN projection in all four trajectories
SOURCE: Global calculator model
**Iron & Steel**

Materials demand growth in trajectories 1, 2, 3 & 4 (1)

---

### Annual Steel production per ambition level (1), by product
(M tons)

<table>
<thead>
<tr>
<th>Trajectories (1) in 2050</th>
<th>2011</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1,518</td>
<td>3,393</td>
<td>2,976</td>
<td>2,777</td>
<td>2,626</td>
</tr>
</tbody>
</table>

#### Trajectories (1) in 2050

- **1**: Reduce
- **2**: Design
- **3**: Switch
- **4**: Recycle

#### Energy efficiency

- **Reduce**
  - **Design**: +123%
  - **Switch**: +96%
  - **Recycle**: +83%
  - **Process**: +73%

#### Fuel Switch

- **Cars & light truck**: +73%
- **Trucks**: +83%
- **Ships**: +96%
- **Rail**: +123%

#### IEA High-low range

- **Cars & light truck EV**
- **Other Buildings**
- **Infrastructure**
- **Mechanical equipments**
- **Appliance**
- **Metal goods**
- **Consumer packaging**
- **Windmills**
- **PV Panels**
- **Electrical Equipment**
- **Pipes**
- **Series**

---

**NOTE:** (1) The population follows the average UN projection in all four trajectories

**SOURCE:** IEA ETP 2012, Global calculator model
### Agenda

#### 2050 evolution of materials and emissions

Materials demand evolution
- Cross sector demand
- Cross sector material switch
- Steel
- **Chemicals**
  - Aluminium
  - Cement
  - Paper & Timber

Reduction potential on the manufacturing processes
- Resulting emissions
- Discussion on ambition levels across sectors
- Discussion on CCS
- Steel
- Chemicals
- Aluminium
- Cement
- Paper, Timber & Other
Significant growth is expected in production volume of the chemical and petrochemical sector

Chemical production volumes forecasts (Mt)

SOURCE: ICCA Catalytic roadmap (data from SRI consulting (IHS))
The largest growth in HVC demand is expected to occur in Africa and Middle East. China already biggest chemical producer worldwide.

Demand for chemical products increases sharply in fast-developing countries.

Likely strongest increase in bulk-chemical production outside Europe.

This regional outlook could be positively impacted by shale gas in some locations (e.g. United States Gulf Coast) (2)

**Regional variability**

**Growths per region to 2050 (%)**

<table>
<thead>
<tr>
<th>Region</th>
<th>Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>&gt;400</td>
</tr>
<tr>
<td>Latin America</td>
<td>&gt;400</td>
</tr>
<tr>
<td>India</td>
<td>340</td>
</tr>
<tr>
<td>Middle East</td>
<td>320</td>
</tr>
<tr>
<td>North America</td>
<td>210</td>
</tr>
<tr>
<td>Europe</td>
<td>170</td>
</tr>
</tbody>
</table>

SOURCE: (1) IEA ETP 2012 (2) ICCA catalytic roadmap
Strong variances are expected between regions (2/2)
This is because the competitiveness levels strongly differ

<table>
<thead>
<tr>
<th>Region</th>
<th>Cost position</th>
<th>Local demand growth</th>
<th>Other crucial factors</th>
<th>Business climate, ease of doing business and corruption</th>
<th>Integration/resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU27</td>
<td>25-50% disadvantage compared to other regions</td>
<td>1-3%</td>
<td>17/14</td>
<td>21/12</td>
<td>Overall, highly integrated and mature industry</td>
</tr>
<tr>
<td>US</td>
<td>10-40% advantage vs. Europe</td>
<td>2-4%</td>
<td>6/25</td>
<td>4/19</td>
<td>Highly integrated and mature industry, new investments ongoing</td>
</tr>
<tr>
<td>China</td>
<td>Higher cost than EU for some products, up to 50% lower cost for others</td>
<td>&gt;10%</td>
<td>44/54</td>
<td>96/80</td>
<td>Less mature industry, not yet fully optimized</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>Cost advantage (up to &gt;50%) for bulk chemicals</td>
<td>~5%</td>
<td>31/39</td>
<td>26/63</td>
<td>Less mature industry, more narrow range of chemicals produced</td>
</tr>
</tbody>
</table>

**NOTE:** Europe represented by Germany in rankings;
1 Calculated as production minus net exports between 2011-2016 using data from IHS Economics;
2 Rank in “Availability of scientists and engineers”, World Economic Forum (WEF);
3 Rank in “Quality of the Education System”, WEF;
4 Rank in the World Bank’s ease of doing business index 2013;
5 Rank in Transparency International’s corruption perception index 2013


- Investments are required to improve energy efficiency and processes
- Investments will be harder to obtain in regions with a lower competitiveness level
### Rationale for expected 2050 chemicals demand

#### Population evolution
- 7 billion people in 2010
- 8-10 billion people in 2050

#### Demand per capita evolution
- **HVC**: from 44 kg/capita in 2010 to 87-105 kg/capita in 2050
- **Ammonia**: from 24 kg/capita in 2010 to 28-32 kg/capita in 2050
- **Methanol**: from 8 kg/capita in 2010 to 22-27 kg/capita in 2050
- **Other chemicals**: are assumed to follow the trend of HVC

#### Regional changes
- The largest growth in HVC demand is expected to occur in Africa and Middle East
- European growth is expected to be much more modest
- Shale gas could have a strong positive impact on US demand

#### Market segment changes
- No major shift between transport, infrastructure and buildings is expected
- But plastics expected to replace other materials in each of these sectors

#### In conclusion
- **IEA ETP 2012 forecast**:
  - 635-872 M tons HVC in 2050
  - 268-310 M tons Ammonia in 2050
  - 213-254 M tons Methanol in 2050

---

**SOURCE:** (1) IEA ETP 2012 (2) With both eyes open
<table>
<thead>
<tr>
<th>Technologies &amp; Products</th>
<th>Evolution driven by</th>
<th>Assumptions (if by product demand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packaging</td>
<td>Product demand lever</td>
<td>80-110% evolution by 2050</td>
</tr>
<tr>
<td>Consumer products</td>
<td>Product demand lever</td>
<td>80-110% evolution by 2050</td>
</tr>
<tr>
<td>Cars &amp; light trucks</td>
<td>Transport model</td>
<td>/</td>
</tr>
<tr>
<td>Windmill (blades in carbon fibre)</td>
<td>Estimate from the supply sector</td>
<td>/</td>
</tr>
<tr>
<td>PV</td>
<td>Estimate from the supply sector</td>
<td>/</td>
</tr>
<tr>
<td>Buildings</td>
<td>Building model</td>
<td>/</td>
</tr>
<tr>
<td>Fertilizers</td>
<td>Land model</td>
<td>/</td>
</tr>
</tbody>
</table>

SOURCE: (1) Global Calculator team assumptions
By 2050, the world population is expected to grow by ~20 to 60%.

World population (billions)

- **High variant**: +57%
- **Medium variant**: +38%
- **Low variant**: +21%

2010-2050 growth (%)

Global calculator growth forecasts
Production according to trajectories 1, 2, 3 & 4
(based on sectors demand, before design, switch & recycling)

Chemicals production per year for different ambition levels (1) (M tons)

<table>
<thead>
<tr>
<th>Year</th>
<th>Trajectory 1</th>
<th>Trajectory 2</th>
<th>Trajectory 3</th>
<th>Trajectory 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
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<tr>
<td>2020</td>
<td></td>
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<tr>
<td>2025</td>
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<tr>
<td>2030</td>
<td></td>
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<tr>
<td>2035</td>
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<tr>
<td>2040</td>
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<tr>
<td>2045</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2050</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Delta 10-50,%

<table>
<thead>
<tr>
<th>Delta</th>
<th>Implied demand per person</th>
</tr>
</thead>
<tbody>
<tr>
<td>+136%</td>
<td>185 kg/person/year</td>
</tr>
<tr>
<td>+86%</td>
<td>146 kg/person/year</td>
</tr>
<tr>
<td>+73%</td>
<td>136 kg/person/year</td>
</tr>
<tr>
<td>+63%</td>
<td>128 kg/person/year</td>
</tr>
</tbody>
</table>

NOTE: (1) The population follows the average UN projection in all four trajectories
SOURCE: Global calculator model

Figures of July 2014
Annual Chemical production per ambition level\(^{(1)}\), by product (M tons)

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>2011</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,765</td>
<td>1,220</td>
<td>1,295</td>
<td>1,390</td>
<td>1,765</td>
<td>749</td>
</tr>
</tbody>
</table>

**Trajectories\(^{(1)}\) in 2050**

**NOTE:** (1) The population follows the average UN projection in all four trajectories

**SOURCE:** IEA ETP 2012, Global calculator model
2050 evolution of materials and emissions
Materials demand evolution
- Cross sector demand
- Cross sector material switch
- Steel
- Chemicals
- Aluminium
  - Cement
  - Paper & Timber
Reduction potential on the manufacturing processes
- Resulting emissions
- Discussion on ambition levels across sectors
- Discussion on CCS
- Steel
- Chemicals
- Aluminium
- Cement
- Paper, Timber & Other
Aluminium
Materials demand growth in trajectories 1, 2, 3 & 4 (1)

Annual Aluminium production per ambition level(1), by product
(M tons)

Trajectories(1) in 2050

Aluminium sector will gain from product switch

NOTE: (1) The population follows the average UN projection in all four trajectories
SOURCE: IEA ETP 2012, Global calculator model
2050 evolution of materials and emissions

Materials demand evolution
  • Cross sector demand
  • Cross sector material switch
  • Steel
  • Chemicals
  • Aluminium

**Cement**
  • Paper & Timber

Reduction potential on the manufacturing processes
  • Resulting emissions
  • Discussion on ambition levels across sectors
  • Discussion on CCS
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper, Timber & Other
As income/person increases, cement demand increases and then decreases

Cement per capita consumption as function of GDP per capita (kg, US$, year 2011)\(^{(1)}\)

Demand for cement is often correlated to national incomes, up to around $20,000/person, but then declines, when demand for new buildings and infrastructure has been satisfied \(^{(1,2)}\)

SOURCES: (1) International Cement Review, Global cement industry trends
(2) With both eyes open
## Cement demand drivers have been identified

<table>
<thead>
<tr>
<th>Driver</th>
<th>Rationale</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demography</td>
<td>Per capita consumption is ~450kg</td>
<td>Direct correlation</td>
</tr>
<tr>
<td>Income</td>
<td>Increase with GDP growth up to ~$20k/person, but then declines, when demand for new buildings and infrastructure has been satisfied</td>
<td>Difficult correlation, as evolution should be modelled per region</td>
</tr>
<tr>
<td>New buildings (residential &amp; commercial, &amp; other)</td>
<td>420 kg cement /m² building 1900 kg concrete / m² of buildings (1)</td>
<td>Direct correlation (includes the demography and income)</td>
</tr>
<tr>
<td>New infrastructure</td>
<td>450 kg cement /m² building ? 1900 kg concrete per m² of buildings (1)</td>
<td>Direct correlation (includes the demography and income) but iteration loop Correlated in model to: • Travel (passenger +freight) evolution • Population (to remove because of double count)</td>
</tr>
</tbody>
</table>

SOURCE: (1) with both eyes open
The IEA expects Cement production increase in all scenarios in most regions except for China which starts very high.

Production evolution per scenario per region for Cement (Mton)

- **2011**: 3,635
  - **Low**: 4,400
  - **High**: 5,521

**2050**
- **Low**: +21%
- **High**: +52%

**Source**: ETP 2012, IEA

**Note**: IEA figures of 2009 per geographic area have been extrapolated to 2011 using the trends provided in International Cement Review, Global cement industry trends.
### Rationale for expected 2050 cement demand

| Population evolution | 7 billion people in 2010\(^{(3)}\)  
<table>
<thead>
<tr>
<th></th>
<th>8-10 billion people in 2050 (^{(3)})</th>
</tr>
</thead>
</table>
| Demand per capita evolution | Per capita  
|                      | • 450 kg of cement per capita in 2011  
|                      | • 470-590 kg of cement per person by 2050 |
| Regional changes     | Per capita  
|                      | • Decrease in China (currently 1218) and Korea (currently 1028)  
|                      | • Increase in other non-OECD countries (from 218 to 480-570)  
|                      | In total  
|                      | • Cement demand is going to be driven by demand in India and China \(^{(2)}\)  
|                      | • Cement production more than triples between 2009 and 2050 in India, Africa and other developing countries in Asia (excluding China), with the result that about 45% of all production in 2050 will be in these countries\(^{(1)}\) |
| Market segment changes | No major shift between infrastructure and buildings is expected |
| In conclusion        | • IEA ETP 2012 has 4500Mt to 5500Mt in 2050\(^{(2)}\) |

**SOURCE:** (1) IEA ETP 2012 (2) With both eyes open (3) UN projection scenarios
By 2050, the world population is expected by the UN to grow by ~20 to 60%.

World population (billions)

- **High variant**: +57%
- **Medium variant**: +38%
- **Low variant**: +21%

**Source:** http://esa.un.org/unpd/wpp/unpp/panel_population.htm 2012 revision
Model growth forecasts
Production according to trajectories 1, 2, 3 & 4
(before design, switch & recycling)

Cement production per year for different ambition levels (1) (M tons)

<table>
<thead>
<tr>
<th>Year</th>
<th>Trajectory 1</th>
<th>Trajectory 2</th>
<th>Trajectory 3</th>
<th>Trajectory 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>522 kg</td>
<td>5,220 kg</td>
<td>4,570 kg</td>
<td>3,480 kg</td>
</tr>
<tr>
<td>2015</td>
<td>912 kg</td>
<td>9,120 kg</td>
<td>4,570 kg</td>
<td>3,480 kg</td>
</tr>
<tr>
<td>2020</td>
<td>1,350 kg</td>
<td>13,500 kg</td>
<td>5,220 kg</td>
<td>3,480 kg</td>
</tr>
<tr>
<td>2025</td>
<td>1,800 kg</td>
<td>18,000 kg</td>
<td>6,630 kg</td>
<td>3,480 kg</td>
</tr>
<tr>
<td>2030</td>
<td>2,250 kg</td>
<td>22,500 kg</td>
<td>8,040 kg</td>
<td>3,480 kg</td>
</tr>
<tr>
<td>2035</td>
<td>2,700 kg</td>
<td>27,000 kg</td>
<td>9,450 kg</td>
<td>3,480 kg</td>
</tr>
<tr>
<td>2040</td>
<td>3,150 kg</td>
<td>31,500 kg</td>
<td>10,860 kg</td>
<td>3,480 kg</td>
</tr>
<tr>
<td>2045</td>
<td>3,600 kg</td>
<td>36,000 kg</td>
<td>12,270 kg</td>
<td>3,480 kg</td>
</tr>
<tr>
<td>2050</td>
<td>4,050 kg</td>
<td>40,500 kg</td>
<td>13,680 kg</td>
<td>3,480 kg</td>
</tr>
</tbody>
</table>

Delta 10-50%,

| Trajectory 1 | +140% |
| Trajectory 2 | +74%  |
| Trajectory 3 | +20%  |
| Trajectory 4 | -9%   |

Implied demand per person

<table>
<thead>
<tr>
<th></th>
<th>912 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>/person/year</td>
<td>663 kg</td>
</tr>
<tr>
<td></td>
<td>457 kg</td>
</tr>
<tr>
<td></td>
<td>348 kg</td>
</tr>
</tbody>
</table>

NOTE: (1) The population follows the average UN projection in all four trajectories
SOURCE: IEA ETP 2012, Global calculator model
Cement
Materials demand growth in trajectories 1, 2, 3 & 4 (1)

Annual Cement production per ambition level(1), by product
(M tons)

2011  |  1  |  2  |  3  |  4  |
---|---|---|---|---|
3,635 | 1,200 | 1,424 | 1,510 | 3,320 |
1,200 | 618 | 830 | 1,316 | 1,121 |
1,818 | 5,581 | 3,989 | 2,808 | 2,006 |
8,708 | 1,704 | 6,329 | 4,360 | -9%

IEA High-low range

Reduce
Design
Switch
Recycle
Process
Fuel Switch
Energy efficiency
CCS

NOTE: (1) The population follows the average UN projection in all four trajectories
SOURCE: IEA ETP 2012, Global calculator model
Agenda

2050 evolution of materials and emissions
Materials demand evolution
  • Cross sector demand
  • Cross sector material switch
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper & Timber

Reduction potential on the manufacturing processes
  • Resulting emissions
  • Discussion on ambition levels across sectors
  • Discussion on CCS
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper, Timber & Other
### Paper

**Materials demand growth in trajectories 1, 2, 3 & 4**

#### Annual Paper production per ambition level, by product (M tons)

<table>
<thead>
<tr>
<th>Trajectories</th>
<th>Print &amp; Graphic Paper</th>
<th>Consumer packaging</th>
<th>Other Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>611</td>
<td>263</td>
<td>73</td>
</tr>
<tr>
<td>1</td>
<td>396</td>
<td>415</td>
<td>111</td>
</tr>
<tr>
<td>2</td>
<td>360</td>
<td>377</td>
<td>101</td>
</tr>
<tr>
<td>3</td>
<td>754</td>
<td>339</td>
<td>91</td>
</tr>
<tr>
<td>4</td>
<td>670</td>
<td>288</td>
<td>80</td>
</tr>
</tbody>
</table>

**IEA High-low range**

(+51%) 922 (+37%) 838 (+23%) 754 (+10%) 670

**Trajectories** in 2050

1. Design
2. Fuel Switch
3. Energy efficiency
4. CCS

**NOTE:** (1) The population follows the average UN projection in all four trajectories

**SOURCE:** IEA ETP 2012, Global calculator model
Timber
Materials demand growth in trajectories 1, 2, 3 & 4 (1)

Annual Timber production per ambition level(1), by product
(M tons)

Trajectories(1) in 2050

NOTE: (1) The population follows the average UN projection in all four trajectories
SOURCE: IEA ETP 2012, Global calculator model
2050 evolution of materials and emissions

Materials demand evolution
  • Cross sector demand
  • Cross sector material switch
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper & Timber

Reduction potential on the manufacturing processes
  • Resulting emissions
  • Discussion on ambition levels across sectors
  • Discussion on CCS
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper, Timber & Other
2050 evolution of materials and emissions
Materials demand evolution
• Cross sector demand
• Cross sector material switch
• Steel
• Chemicals
• Aluminium
• Cement
• Paper & Timber
Reduction potential on the manufacturing processes
• Resulting emissions
• Discussion on ambition levels across sectors
• Discussion on CCS
• Steel
• Chemicals
• Aluminium
• Cement
• Paper, Timber & Other
For the materials production, ~50 actions are being considered

### List of actions & levers assessed

<table>
<thead>
<tr>
<th>Industry groups</th>
<th>Design</th>
<th>Switch</th>
<th>Recycle</th>
<th>Process improvements</th>
<th>Alternatives</th>
<th>Energy efficiency</th>
<th>CCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Product Design</td>
<td>• Switch to alu, fibres &amp; timber</td>
<td>• Product recycling</td>
<td>• Carbon materials reduction</td>
<td>• Coke to gas injection</td>
<td>• Material efficiency</td>
<td>• CCS</td>
</tr>
<tr>
<td></td>
<td>• High strength steel</td>
<td></td>
<td>• % scrap based (for each various technologies exist)</td>
<td>• Portion of Classic BOF/Top gas recycling &amp; Hisarna/oxygen/EAF DRI/EAF scrap</td>
<td>• Coal PCI to biomass</td>
<td>• Energy efficiency (EE)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Smelt reduction, Hydrogen, Electrolysis</td>
<td></td>
<td>• CHP</td>
<td></td>
</tr>
<tr>
<td>Chemicals</td>
<td>All</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Product design</td>
<td>• Switch from steel, alu, cement</td>
<td>• Product recycling</td>
<td>• Process intensification</td>
<td>• Oil to gas</td>
<td>• Clustering &amp; integration</td>
<td>• CCS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Material recycling</td>
<td>• Green chemistry</td>
<td>• Catalyst optimization</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ammonia</td>
<td>• Fertilizers composition</td>
<td>• Included in energy efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methanol</td>
<td>• Green chemistry</td>
<td>• Included in energy efficiency</td>
<td>• Hydrogen production by electrolysis</td>
<td>• Hydrogen</td>
<td>• EE</td>
<td>• CCS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Natural gas or biomass</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>• Switch from steel, alu, cement</td>
<td>• Included in energy efficiency</td>
<td>• Switch Mercury to membrane</td>
<td>• Coal &amp; oil to Waste &amp; biomass</td>
<td>• EE</td>
<td>• CCS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Material recycling</td>
<td>• Coal &amp; oil to gas &amp; biomass</td>
<td>• Coal &amp; oil to gas</td>
<td>• CHP/heat recovery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>• Product design</td>
<td>• Switch to fibres</td>
<td>• Product recycling</td>
<td>• Included in energy efficiency</td>
<td>• Gas injection</td>
<td>• EE</td>
<td>• CCS</td>
</tr>
<tr>
<td></td>
<td>• Product design</td>
<td>• Material recycling</td>
<td>• Dry process</td>
<td>• Coal &amp; oil to Waste &amp; biomass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Switch to Timber &amp; Plastics</td>
<td>• Composed/metallurgical cement</td>
<td>• Coal &amp; oil to gas</td>
<td>• Coal &amp; oil to biomass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulp &amp; paper</td>
<td>• /</td>
<td>• /</td>
<td>• More recycled paper</td>
<td>• Black liquor gasification</td>
<td>• EE</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Other cellulose sources</td>
<td>• Drying innovation</td>
<td>• CHP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Bio-refineries</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timber</td>
<td>• Product design</td>
<td>• Switch from steel &amp;cement</td>
<td>• /</td>
<td>• Black liquor gasification</td>
<td>• Coal &amp; oil to gas</td>
<td>• EE</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Coal &amp; oil to biomass</td>
<td>• CHP</td>
<td></td>
</tr>
</tbody>
</table>

SOURCE: Climact
Total GHG Emissions in trajectories 1, 2, 3 & 4

Total GHG emissions per year, by technology
(M tons CO$_2$e$^{(2)}$)

Trajectories$^{(1)}$ in 2050

NOTE: (1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions

SOURCE: IEA ETP 2012, Global calculator model
### Total GHG Emissions in trajectories 1, 2, 3 & 4

#### Total GHG emissions per year, by technology

(M tons CO\textsubscript{2}e)

<table>
<thead>
<tr>
<th>Technology</th>
<th>2011</th>
<th>2050 Trajectory 1</th>
<th>2050 Trajectory 2</th>
<th>2050 Trajectory 3</th>
<th>2050 Trajectory 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper: Recycled</td>
<td>9,632</td>
<td>5,997 (128%)</td>
<td>4,472 (70%)</td>
<td>3,640 (29%)</td>
<td>2,808 (-1%)</td>
</tr>
<tr>
<td>Paper: Virgin</td>
<td>12,467</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper: Pulp</td>
<td>22,001</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium: Alumina</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium: Secondary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium: Primary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel: Electric</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel: ElectricDRI</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel: Oxygen</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Steel: Oxygen Hisarna</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemicals: HVC</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemicals: Methanol</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemicals: Ammonia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemicals: Others</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other industries</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Trajectories\textsuperscript{(1)} in 2050**

1. +128%
2. +70%
3. +29%
4. -1%

---

**Note:**

1. The population follows the average UN projection in all four trajectories
2. Assuming biomass emits, not including electricity related emissions

**Source:** IEA ETP 2012, Global calculator model
Total GHG Emissions in trajectories 1, 2, 3 & 4

Total GHG emissions per year, by technology
(M tons CO$_2$e)

Trajectories$^{(1)}$ in 2050

NOTE:  
(1) The population follows the average UN projection in all four trajectories  
(2) Assuming biomass emits, not including electricity related emissions  
SOURCE: IEA ETP 2012, Global calculator model
Total GHG Emissions in trajectories 1, 2, 3 & 4

Total GHG emissions per year, by technology (M tons CO$_2$e)

Trajectories$^{(1)}$ in 2050

NOTES:
(1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions
SOURCE: IEA ETP 2012, Global calculator model
Total GHG Emissions in trajectories 1, 2, 3 & 4

Total GHG emissions per year, by technology (M tons CO$_2$e)

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>2011</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>9,632</td>
<td>22,024</td>
<td>15,570</td>
<td>11,209</td>
<td>7,384</td>
</tr>
</tbody>
</table>

- **+129%**
- **+62%**
- **+16%**
- **-23%**

Trajectories$^{(1)}$ in 2050

**NOTE:**
(1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions

**SOURCE:** IEA ETP 2012, Global calculator model
Total GHG Emissions in trajectories 1, 2, 3 & 4

Total GHG emissions per year, by technology
(M tons CO$_2$e)

Trajectories$^{(1)}$ in 2050

Biomass impact outweighs other fuel switches

NOTE:  
(1) The population follows the average UN projection in all four trajectories  
(2) Assuming biomass emits, not including electricity related emissions  
SOURCE: IEA ETP 2012, Global calculator model
Total GHG Emissions in trajectories 1, 2, 3 & 4

Total GHG emissions per year, by technology (M tons CO$_2$e)

Trajectories$^{(1)}$ in 2050

An emission increase is expected here because of the additional gas consumption in chemicals and paper for the CHPs (while electricity emissions are not accounted for in this slide).

NOTE:
(1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions
SOURCE: IEA ETP 2012, Global calculator model
Total
GHG Emissions in trajectories 1, 2, 3 & 4

Total GHG emissions per year, by technology
(M tons CO$_2$e)

<table>
<thead>
<tr>
<th>Year</th>
<th>Total GHG Emissions in trajectories 1, 2, 3 &amp; 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>9,690</td>
</tr>
<tr>
<td>1</td>
<td>22,065</td>
</tr>
<tr>
<td>2</td>
<td>11,748</td>
</tr>
<tr>
<td>3</td>
<td>6,035</td>
</tr>
<tr>
<td>4</td>
<td>1,887</td>
</tr>
</tbody>
</table>

Trajectories$^{(1)}$ in 2050

NOTE:
(1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions
SOURCE: IEA ETP 2012, Global calculator model
Total
GHG Emissions evolutions in trajectories 1, 2, 3 & 4

Total GHG emissions for different lever ambition levels
(MtonCO₂e)

NOTE:  
(1) The population follows the average UN projection in all four trajectories  
(2) Assuming biomass emits, not including electricity related emissions

SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Details for ambition level 3 (then detailed per industry)

Total production for ambition level 3
(M tons, % of 2011)

<table>
<thead>
<tr>
<th>Year</th>
<th>Original</th>
<th>Design</th>
<th>Switch</th>
<th>Recycling</th>
<th>Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>8.405</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.656</td>
<td>-2.310</td>
<td></td>
<td>-259</td>
<td>-9.588</td>
</tr>
</tbody>
</table>

Trajectories(1) in 2050

NOTE: (1) The population follows the average UN projection in all four trajectories
(2)Assuming biomass emits, not including electricity related emissions
SOURCE: IEA ETP 2012, Global calculator model
Total GHG emissions in 2050, for ambition level 3\(^{(1,2)}\), using different levers\(^{(3)}\)
(MtCO\(_2\)e, % of 2010)

NOTES:  
(1) The population follows the average UN projection in all four trajectories  
(2) Excluding biomass related reductions & electricity related emissions  
(3) Other sectors are impacted by these transitions (e.g. additional emissions are created in the aluminium and plastics sectors)

Percentage reductions are calculated vs the 2010 baseline

SOURCE: IEA ETP 2012, Global calculator model
2050 evolution of materials and emissions

Materials demand evolution
• Cross sector demand
• Cross sector material switch
• Steel
• Chemicals
• Aluminium
• Cement
• Paper & Timber

Reduction potential on the manufacturing processes
• Resulting emissions
  • Discussion on ambition levels across sectors
  • Discussion on CCS
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper, Timber & Other
## Total GHG Emissions in trajectories 3

### Total emissions, along each step (by materials)
(M tons CO\textsubscript{2}e, (% evolution vs 2011))

<table>
<thead>
<tr>
<th>Material</th>
<th>2011</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Demand</td>
</tr>
<tr>
<td>Steel</td>
<td>3.039</td>
<td>5558 (83%)</td>
</tr>
<tr>
<td>Chemicals &amp; petrochemicals</td>
<td>1.286</td>
<td>2223 (73%)</td>
</tr>
<tr>
<td>Aluminium</td>
<td>150</td>
<td>347 (131%)</td>
</tr>
<tr>
<td>Cement</td>
<td>2.206</td>
<td>2646 (20%)</td>
</tr>
<tr>
<td>Pulp &amp; Paper</td>
<td>393</td>
<td>485 (23%)</td>
</tr>
<tr>
<td>Timber</td>
<td>348</td>
<td>419 (20%)</td>
</tr>
<tr>
<td>Other industries</td>
<td>2.210</td>
<td>3787 (71%)</td>
</tr>
<tr>
<td>Total</td>
<td>9.632</td>
<td>15465 (61%)</td>
</tr>
</tbody>
</table>

Knowing the different sector characteristics, do these reductions seem balanced across sectors?

Let’s decompose this slide step by step.
Global Calculator

Total
GHG Emissions in trajectories 3(1)

Change in GHG emissions(2) vs 2011 after this lever
(\% vs 2011)

All sectors started at 0\% in 2011

Steel | Chemicals | Aluminium | Cement | Paper | Timber | Others | Total
--- | --- | --- | --- | --- | --- | --- | ---
83 | 73 | 131 | 20 | 23 | 20 | 71 | 61

NOTE:
(1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions
SOURCE: IEA ETP 2012, Global calculator model
## Global Calculator

### Total

**GHG Emissions in trajectories 3\(^{(1)}\)**

#### Change in GHG emissions\(^{(2)}\) vs 2011 after this lever (% vs 2011)

<table>
<thead>
<tr>
<th>Material</th>
<th>Reduce</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>83</td>
<td>46</td>
</tr>
<tr>
<td>Chemicals</td>
<td>73</td>
<td>42</td>
</tr>
<tr>
<td>Aluminium</td>
<td>85</td>
<td>20</td>
</tr>
<tr>
<td>Cement</td>
<td>20</td>
<td>23</td>
</tr>
<tr>
<td>Paper</td>
<td>131</td>
<td>20</td>
</tr>
<tr>
<td>Timber</td>
<td>71</td>
<td>37</td>
</tr>
<tr>
<td>Others</td>
<td>61</td>
<td>29</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>85</td>
<td>20</td>
</tr>
</tbody>
</table>

**NOTE:**
1. The population follows the average UN projection in all four trajectories
2. Assuming biomass emits, not including electricity related emissions

**SOURCE:** IEA ETP 2012, Global calculator model
**Total**

GHG Emissions in trajectories 3\(^{(1)}\)

---

**Change in GHG emissions\(^{(2)}\) vs 2011 after this lever**

(\% vs 2011)

- **Steel**
  - Reduce: 83
  - Design: 46
  - Switch: 39

- **Chemicals**
  - Reduce: 73
  - Design: 42
  - Switch: 46

- **Aluminium**
  - Reduce: 131
  - Design: 85
  - Switch: 107

- **Cement**
  - Reduce: 20
  - Design: 23
  - Switch: 11

- **Paper**
  - Reduce: 11
  - Design: 11
  - Switch: 11

- **Timber**
  - Reduce: 20
  - Design: 60
  - Switch: 71

- **Others**
  - Reduce: 60
  - Design: 37
  - Switch: 37

- **Total**
  - Reduce: 61
  - Design: 29
  - Switch: 28

---

**NOTE:**

1. The population follows the average UN projection in all four trajectories.
2. Assuming biomass emits, not including electricity related emissions.

**SOURCE:** IEA ETP 2012, Global calculator model

---

The fact carbon fibres emit more is currently not modelled.
Total
GHG Emissions in trajectories 3\(^{(1)}\)

Change in GHG emissions\(^{(2)}\) vs 2011 after this lever (% vs 2011)

Modelled by reduced demand

<table>
<thead>
<tr>
<th></th>
<th>Steel</th>
<th>Chemicals</th>
<th>Aluminium</th>
<th>Cement</th>
<th>Paper</th>
<th>Timber</th>
<th>Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in GHG</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>emissions(^{(2)}) vs 2011</td>
<td>-4</td>
<td>-14</td>
<td>220</td>
<td>20</td>
<td>131</td>
<td>107</td>
<td>85</td>
<td>2</td>
</tr>
</tbody>
</table>

NOTE: (1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions
SOURCE: IEA ETP 2012, Global calculator model
Global Calculator

Total
GHG Emissions in trajectories 3\(^{(1)}\)

Change in GHG emissions\(^{(2)}\) vs 2011 after this lever
(\% vs 2011)

NOTE:  
(1) The population follows the average UN projection in all four trajectories  
(2) Assuming biomass emits, not including electricity related emissions

SOURCE: IEA ETP 2012, Global calculator model
Change in GHG emissions\(^{(2)}\) vs 2011 after this lever
\(\%\) vs 2011

Biomass increase outweighs the oil to gas switch

NOTE:
(1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions

SOURCE: IEA ETP 2012, Global calculator model

Steel   Chemicals   Aluminium   Cement   Paper   Timber   Others   Total

Biomass is modelled as fossil hydrocarbons at this stage, it is then removed at the end
Change in GHG emissions\(^{(2)}\) vs 2011 after this lever (% vs 2011)

NOTE: (1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions

SOURCE: IEA ETP 2012, Global calculator model
**Total GHG Emissions in trajectories 3**

Change in GHG emissions(2) vs 2011 after this lever (% vs 2011)

**NOTE:**
1. The population follows the average UN projection in all four trajectories
2. Assuming biomass emits, not including electricity related emissions

**SOURCE:** IEA ETP 2012, Global calculator model
### Total GHG Emissions in trajectories 3

**Total emissions, along each step (by technology)**
(M tons CO$_2$e, (% evolution vs 2011))

<table>
<thead>
<tr>
<th>Material</th>
<th>Technology</th>
<th>2011</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Demand</td>
</tr>
<tr>
<td>Steel</td>
<td>Oxygen</td>
<td>2.529</td>
<td>4626 (83%)</td>
</tr>
<tr>
<td></td>
<td>Oxygen Hisarna</td>
<td>-</td>
<td>N/A</td>
</tr>
<tr>
<td>Electric</td>
<td>300</td>
<td>548 (83%)</td>
<td>438 (46%)</td>
</tr>
<tr>
<td>Electric DRI</td>
<td>210</td>
<td>384 (83%)</td>
<td>307 (46%)</td>
</tr>
<tr>
<td>Chemicals &amp; petrochemicals</td>
<td>HVC</td>
<td>324</td>
<td>559 (73%)</td>
</tr>
<tr>
<td></td>
<td>Ammonia</td>
<td>286</td>
<td>495 (73%)</td>
</tr>
<tr>
<td></td>
<td>Methanol</td>
<td>158</td>
<td>273 (73%)</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>518</td>
<td>895 (73%)</td>
</tr>
<tr>
<td>Alumina</td>
<td>Alumina</td>
<td>106</td>
<td>245 (131%)</td>
</tr>
<tr>
<td></td>
<td>Primary</td>
<td>30</td>
<td>70 (131%)</td>
</tr>
<tr>
<td></td>
<td>Secondary</td>
<td>14</td>
<td>33 (131%)</td>
</tr>
<tr>
<td>Cement</td>
<td>Cement</td>
<td>2.206</td>
<td>2646 (20%)</td>
</tr>
<tr>
<td>Pulp &amp; Paper</td>
<td>Pulp</td>
<td>194</td>
<td>240 (23%)</td>
</tr>
<tr>
<td></td>
<td>Virgin</td>
<td>176</td>
<td>217 (23%)</td>
</tr>
<tr>
<td></td>
<td>Recycled</td>
<td>23</td>
<td>28 (23%)</td>
</tr>
<tr>
<td>Timber</td>
<td>Timber</td>
<td>348</td>
<td>419 (20%)</td>
</tr>
<tr>
<td>Other industries</td>
<td>Other industries</td>
<td>2.210</td>
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<tr>
<td>Total</td>
<td>Total</td>
<td>9.632</td>
<td>15465 (61%)</td>
</tr>
</tbody>
</table>

Knowing the different sector characteristics, do these reductions seem balanced across sectors?
2050 evolution of materials and emissions

Materials demand evolution
- Cross sector demand
- Cross sector material switch
- Steel
- Chemicals
- Aluminium
- Cement
- Paper & Timber

Reduction potential on the manufacturing processes
- Resulting emissions
- Discussion on ambition levels across sectors

- Discussion on CCS
  - Steel
  - Chemicals
  - Aluminium
  - Cement
  - Paper, Timber & Other
Carbon Capture & Storage
Projections by region

Capture rate
(MtCO₂/year)

Blue scenario leads to a 4 Gt reduction in 2050, while total additional costs add up to 3 trillion USD by 2050.

SOURCE: IEA ETP 2012, IEA UNIDO 2011
Carbon Capture & Storage
Blue roadmap goes from 60 projects in 2020 to 1800 in 2050

Capture rate
(MtCO$_2$ captured/year)
Carbon Capture & Storage
Industry ambition 3 leads to a similar capture rate

**Capture rate**
(MtCO₂ captured/year)

- **Steel: Oxygen**
- **Steel: Oxygen Hisarna**
- **Steel: Electric**
- **Steel: ElectricDRI**
- **Chemicals: HVC**
- **Chemicals: Ammonia**
- **Chemicals: Methanol**
- **Chemicals: Others**
- **Aluminium: Alumina**
- **Aluminium: Primary**
- **Aluminium: Secondary**
- **Cement**
- **Paper: Pulp**
- **Paper: Virgin**
- **Paper: Recycled**
- **Timber**
- **Other industries**

**NOTE:** Biomass is considered as fossil fuel & electricity emissions are not counted in this view.

**SOURCE:** Global Calculator model.
Typical ranges of costs of emission reductions from industrial applications of CCS (USD/tCO$_2$e avoided)

In addition, an electricity consumption of 0.33 TWh/MtCO$_2$e captured is modelled

NOTE: The range of costs shown here reflect the regional average costs of applying CCS in each sector, and, therefore, the overall cost of abatement in a sector will be affected by the assumed level of CCS uptake in each sector (IEA, 2009 and IEA and UNIDO 2011). These costs include the cost of capture, transport and storage, but do not assume that storage generates revenues (i.e. CO$_2$ storage through enhanced oil recovery (EOR) is not considered as a storage option.)

SOURCE: ETP 2012, IEA
### Sector implications for a blue scenario equivalent

<table>
<thead>
<tr>
<th>Sector</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Iron &amp; Steel</strong></td>
<td>• Improve the economics of capture techniques in the iron &amp; steel sector</td>
</tr>
<tr>
<td></td>
<td>• Equip 75% of new production with CCS by 2030 in OECD (50% in non OECD)</td>
</tr>
<tr>
<td>**Chemicals</td>
<td>• Compile inventory of opportunities &amp; assess costs</td>
</tr>
<tr>
<td>(High Purity)</td>
<td>• Perform demonstration projects involving hydrogen, ammonia &amp; ethylene processes</td>
</tr>
<tr>
<td><strong>Aluminium</strong></td>
<td>• Assumed similar to steel (relatively)</td>
</tr>
<tr>
<td><strong>Cement</strong></td>
<td>• Improve the economics of capture techniques under flue gas conditions which are typical for the cement sector</td>
</tr>
<tr>
<td></td>
<td>• Perform full scale plant between 2015 &amp; 2020</td>
</tr>
<tr>
<td><strong>Paper</strong></td>
<td>• Assumed similar to Biomass sector objectives (relatively)</td>
</tr>
<tr>
<td></td>
<td>• R&amp;D on biomass gasification processes</td>
</tr>
<tr>
<td></td>
<td>• Realise full scale plants by 2020</td>
</tr>
<tr>
<td><strong>Timber</strong></td>
<td>• Assumed similar to paper</td>
</tr>
</tbody>
</table>

**SOURCE:** IEA UNIDO 2011
2050 evolution of materials and emissions

Materials demand evolution
  • Cross sector demand
  • Cross sector material switch
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper & Timber

Reduction potential on the manufacturing processes
  • Resulting emissions
  • Discussion on ambition levels across sectors
  • Discussion on CCS

• Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper, Timber & Other
3 technologies are currently used to make most of the steel

NOTE: (1) DRI is illustrated here with the Electric arc furnaces. It can also be performed with Blast furnaces.
SOURCE: GSV, World Steel, Climact
Steel emissions are being modelled

Steel emission tree

- Steel
  - Oxygen steel
  - DRI EAF
  - Top Gas / HIsarna
  - Electric steel
    - Production
    - Energy Intensity
    - Process intensity
    - Production
    - Energy Intensity
    - Process intensity
    - Production
    - Energy Intensity
    - Process intensity
Material demand / product: Design, Switch & Recycling levers are assessed

List of actions & levers assessed

Design
- Changing product and material specifications to answer the same needs with less materials
  - Smarter design with similar steel grades
  - Increase proportion of high strength steel

Switch
- Change materials to enable a low carbon product (over the product lifetime)
  - In vehicles: To aluminium & to plastics
  - In buildings/Infr.: To green plastics & to timber

Recycling
- Recycle the product or the material
  - Product recycling
  - Material recycling: Electric arc furnace

SOURCE: Climact
Design: Smarter design & high strength steel increase
Better designs & new steel grades can lower the mass required to fulfil specifications

Smarter design

- Smarter design can enable to reduce the materials demand (including steel)
- Examples include:
  - Lighter vehicles
  - Buildings with less redundancies

High strength steel

- At world level, estimates mention the use of high strength steel to be:
  - Globally at around 20% with a potential of 50%
  - In the automotive industry above 50% already

High strength steel characteristics

Requires less steel

- High strength steel (also called « Hard steel » or « High processability steels ») can be substituted to normal steel but requiring 30% less steel to meet the same standards (e.g. to enable the end product to be as solid)
- For automotive manufacturers, the use of Advanced and Ultra High-Strength steels (AHSS and UHSS), allow to reduce mass of the vehicles by 17% to 25% while maintaining safety standards (2)
- At global level, this is modelled by a reduction in steel production. At local level, we would assume the installations which would invest in the technology would continue to produce at full capacity.

Impact on the steel production

- Producing higher strength steel does not produce significantly more CO\textsubscript{2}e emissions per ton of steel produced. It is estimated that treatments like reheating and galvanizing could increase consumption by 2-5% (with an unknown upside) (1,3)
- High strength steel tends to depend more on the primary steel. But this is not exclusive; high strength steel can be made from the secondary steel (3)

NOTE: Producing higher strength steel does not affect the industry profitability because even if less is required, it is also sold with a higher margin per ton

SOURCE: (1) Arcelor, (2) WorldSteel fact sheet the 3Rs (Reduce, Reuse, Recycle), based
A) on ULSAB research (WorldAutoSteel), carmakers’ own body structure designs
Climact, interview expert in the context of Belgium Low Carbon 2050, (3) Global Calculator steel consultations
Share of high strength steel (%)

- High strength steel is modelled requiring 30% less steel
- Upside on smart design and downside on additional specific consumption of high strength steel not modelled and assumed to balance one another

**Lever cost (2)**

<table>
<thead>
<tr>
<th></th>
<th>€/t crude steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input (fuel &amp; material)</td>
<td>-x</td>
</tr>
<tr>
<td>Other opex</td>
<td>0</td>
</tr>
<tr>
<td>Capex</td>
<td>+x</td>
</tr>
</tbody>
</table>

NOTE: (2) Assuming the additional capex is balanced by the input reduction
SOURCE: Climact national consultations
**Material switch**
Steel is a relatively cheap material

**Embodied energy**
(Gj/t)

<table>
<thead>
<tr>
<th>Material</th>
<th>Embodied energy (Gj/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>200</td>
</tr>
<tr>
<td>Steel</td>
<td>100</td>
</tr>
<tr>
<td>Concrete</td>
<td>10</td>
</tr>
<tr>
<td>Plastics</td>
<td>20</td>
</tr>
<tr>
<td>Stone</td>
<td>150</td>
</tr>
<tr>
<td>Wood</td>
<td>100</td>
</tr>
</tbody>
</table>

**Relative useful costs**
(relative to steel at 100%)

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative useful costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>350%</td>
</tr>
<tr>
<td>Steel</td>
<td>100%</td>
</tr>
<tr>
<td>Concrete</td>
<td>10%</td>
</tr>
<tr>
<td>Plastics</td>
<td>20%</td>
</tr>
<tr>
<td>Stone</td>
<td>217%</td>
</tr>
<tr>
<td>Wood</td>
<td>180%</td>
</tr>
</tbody>
</table>

- Compared to other metals, steel has lower embodies energy and costs
- Concrete and stone are not substitutes as they are weak in tension
- Aluminium does not score well but enables lighter products

**Embodied energy** to convert the material in useful form
**Relative cost per tonne to convert the materials in useful form**

NOTE: (1) Refer to “With both eyes open” for more details on the definition of useful costs
SOURCE: (1) With both eyes open
### Material switch
Steel can be substituted to enable less CO\textsubscript{2} emissions along product life cycles

#### Materials which can replace /be replaced by steel

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Steel replacement assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td><strong>Vehicles (8%)</strong></td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
<td></td>
</tr>
</tbody>
</table>

- **Aluminium**
  - Density
  - Less strong, less recyclable
  - Higher cost & embodied energy
  - Up to 20% steel can be replaced by aluminium
- **Concrete**
  - Steel compatibility (rebar), Low cost & embodied energy, no corrosion
  - Weak in tension
  - Non recyclable
  - Not applicable
- **Plastics** (Composite materials, glass/ carbon fibres reinforced epoxies)
  - Density, Strength per density (of some plastic types)
  - Lower recyclability
  - Less reparable (e.g. carbon fibre cars)
  - Higher embodied energy
  - Difficult manufacturing
  - Up to 20% steel can be replaced by carbon fibre (HVC)
- **Stone & Masonry**
  - Lower embodied emissions
  - Must be reinforced with mortar (from cement)
  - Cannot be reinforced or moulded into shapes
  - Not applicable
- **Timber**
  - Strength and stiffness per density (1)
  - Less durable, requires protection against fire and rot, less stable
  - Lower, uniformity
  - Up to 20% steel can be replaced by timber in buildings

(1) With both eyes open (Orr et al. (2010), research of efficient concrete shapes)
## Material switch

### Proposed lever ambitions

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
<tbody>
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<td>Minimum effort (following current regulation)</td>
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</tr>
</tbody>
</table>

- **Vehicles:** 0% switch  
  - **Buildings:** 0% switch

- **Vehicles:** 5% substitution by aluminium, 5% by plastics  
  - **Buildings/Infra:** 5% substitution by timber

- **Vehicles:** 10% substitution by aluminium, 10% by plastics  
  - **Buildings/Infra:** 10% substitution by timber

- **Vehicles:** 20% substitution by aluminium, 20% by plastics  
  - **Buildings/Infra:** 20% substitution by timber

### Lever cost

<table>
<thead>
<tr>
<th>Material switch</th>
<th>Lever cost (£/t steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel ➔ Aluminium</td>
<td>0</td>
</tr>
<tr>
<td>Steel ➔ Timber</td>
<td>0</td>
</tr>
<tr>
<td>Steel ➔ Plastics</td>
<td>0</td>
</tr>
</tbody>
</table>

**NOTE:**
1. Amount of one material required to replace another material is approximated through the specific Young modulus.
2. Assumption this material switch does not impact the product life.
Rationale on reusing the products

- When using steel based products, both the products (cars, appliances, etc.) and the materials (scrap steel) can be reused.
- The products reusing lever is currently not modelled, this is due to lack of data, and perception this lever has a lower impact.

Illustrations on Products
- In North America approximately 33% of the straight railway track sections purchased comes from used rail that is disassembled at redevelopment sites (1)

SOURCE: (1) Worldsteel factsheet on the 3Rs (Reduce, Reuse, Recycle)
### Rationale on steel recycling

- Steel is the world’s most recycled material \(^{(3)}\)
- We are still a long way from collecting all our discarded metals for recycling
  - Steel reinforcement bars in subsurface concrete (e.g. foundations and tunnels) are currently not extracted at end of life \(^{(2)}\)
  - Deep sea line pipes are not removed at the end of their lives
- 100-150$/ton scrap is required in order to have economically viable recovery of scrap (high scrap prices will drive up the scrap collection price) \(^{(4)}\)
- Maximum recycling rates for steel might be at 90% \(^{(1)}\)

### Worldsteel recycling rate targets \(^{(3)}\)

(2007 est. and 2050 objectives, %)

<table>
<thead>
<tr>
<th>Application</th>
<th>2007 est.</th>
<th>2050 Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>85%</td>
<td>90%</td>
</tr>
<tr>
<td>Automotive</td>
<td>85%</td>
<td>95%</td>
</tr>
<tr>
<td>Machinery</td>
<td>90%</td>
<td>95%</td>
</tr>
<tr>
<td>Appliances</td>
<td>50%</td>
<td>75%</td>
</tr>
<tr>
<td>Containers</td>
<td>69%</td>
<td>75%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>83%</strong></td>
<td><strong>90%</strong></td>
</tr>
</tbody>
</table>

\(^{(1)}\) Professor Robert Ayres (INSEAD) (2) (with both eyes open) (3) Worldsteel fact sheet, the 3 Rs(Reduce, Reuse, Recycle) (4) Global Calculator consultations
Materials recycling: Scrap based steel
Recycled steel is at~30% well below the 80%, this is because of a) the limited availability and b) the time lag

Historic evolution of the Electric steel production in the total crude steel production (%) (1)

- Steel Production and therefore reserves are increasing worldwide (2)
- The steel stock should, by some estimates, become self sufficient in one century
- World reduction is explained by growth in developing countries
- Historically, the proportion of electric steel has increased in developed geographic areas; as countries develop, they produce more metal scrap
- Fast growing countries favour oxygen steel production (as the availability of scrap is not sufficient to meet the rapidly growing production)
- There is a large increasing amount of steel embedded in products that are still in use and have not reached the end of their lifespan. Steel can remain more than 50 years in the lifecycle which creates a lag between production increase and available scrap metal increase (3)

NOTES: (1) the EAF includes the both 100% scrap based EAF as well as EAF that uses DRI and/or hot metal in addition to scrap (3) Length is function of the sector. 50 years is typically applicable in the buildings sector, automotive and consumer goods sector typically have shorter lifetimes
IEA estimates on the availability of scrap in the 2-4-6DS scenarios (Mt)

- Steel scrap is expected to increase by 140-180%.
- In future versions of the model, the scrap availability will be fixed directly in the model.
- Worldsteel forecasts 40% recycled steel in 2050. 50% supply from scrap is a reasonable scenario, but dependent on many factors (e.g. economics for energy, raw materials and scrap prices and cost and overall demand region or country by country etc.)
- Higher scrap estimates (up to 75%), assuming 25% additional by including industrial scrap.
- Scrap availability rate could go much higher by 2100.

SOURCE: IEA ETP 2012, (2) Worldsteel, (3) With Both Eyes open
Materials recycling: Scrap based steel

In lower demand scenario, NTNU & Cambridge scenarios forecast earlier market saturation and higher scrap%

Primary steel flows (from ore)
(Mt/year)

Secondary steel making (from scrap)
(Mt/year)

SOURCE: NTNU & Cambridge University (2014 04 10 International Materials Education Symposium)
EAF increase implications

• The cost /ton of EAF steel is higher (1,3,4) because of the energy consumption (6)
• EAF enables to produce the steel for all applications (7). However, BOF production produces higher quality steel for some applications (e.g. automotive sector) (3)
• High EAF scenarios require higher quality Scrap metals collection
• The reduction of BOF has a negative impact on other industries (e.g. cement uses blast furnaces slag to produce composed/metallurgic cements which emit less CO₂ (2))
• In a world with overcapacity, EAF ovens offer more flexibility to be turned on or off
Materials recycling: Scrap based steel
Proposed lever ambitions

Scrap steel production in the total crude steel production (%)

- Ambition 1
- Ambition 2
- Ambition 3
- Ambition 4

Ambitions reflect the 2050 scrap availability
This is different from the proportion of EAF

SOURCE:
(1) Total production is kept constant but we assume this production is shifted to Electric Arc furnaces
(2) Eurofer 2013, A Steel Roadmap for a Low Carbon Europe 2050
Carbon intensity of material production
Process improvements, fuel mixes, energy efficiency & CCS are then assessed

List of actions & levers assessed

**Process improvement**
- Towards fuels which emit less CO₂
  - Reduction of carboniferous materials
  - Portion of Classic/Top gas recycling & Hisarna in oxygen
  - Portion of DRI/scrap in EAF
  - Smelt reduction potential(1)
  - Electrolysis
  - Hydrogen

**Fuel substitution**
- Modification of processes
  - Coke substitution by gas injection

**Energy efficiency**
- Reduce mechanical and thermal losses
  - Recuperate thermal energy (CHP)
  - Improvements in current process
  - Coal PCI substitution by biomass
  - CHP

**End of pipe technologies**
- Carbon capture and storage
  - CCS implementation
  - CCU

NOTE: Process choice has consequences on applicability of other levers. Some combinations are exclusive whilst others can be added in sequential order.

SOURCE: (1) (redundant with Ulcored while we represent Hisarna in this analysis)
3 Process: Reduction of carboniferous materials
There is limited further potential in reducing the amount of carboniferous materials per ton of steel

Evolution of carboniferous materials to produce liquid iron cast
(Kg CO₂e/t liquid iron cast)

- The amounts of carboniferous materials per ton of steel have been significantly reduced during the last decades
- To date, the blast furnaces in the EU15 use today an average of 0.49 kg of carboniferous materials per kg of liquid iron cast produced\(^{(1)}\), or 115 kg of input materials for 100 kg of steel \(^{(2)}\)

It is considered this lever has no additional potential

SOURCE: (1) ULCOS VDEh Germany, (2) WorldSteel Fact sheet, the 3Rs (reduce, reuse, recycle), Steel consultation Belgium Low Carbon 2050
### Technology

<table>
<thead>
<tr>
<th>Technology</th>
<th>Top gas recycling (+ Carbon capture)</th>
<th>ULCORED + EAF (+ Carbon Capture)</th>
<th>Hlsarna smelter (+ Carbon capture)</th>
<th>Ulcowin – Electrolysis</th>
</tr>
</thead>
</table>
| **Process** | • Recycling CO (reducing agent) from blast furnace waste gas  
• Reduces coke and coal requirements  
• Cokes and sinter production unchanged | • Direct reduction process  
• Uses natural gas as reducing agent  
• No coke required | • Combines all the heat processes in one  
• Direct use of ore and coal: 20% reduction of CO2 – 80% with CC  
• Significant coal savings - partial substitution by biomass, natural gas, or H2  
• Substantial reduction of other emissions | |
| **Maturity** | • Laboratory: done  
• Pilot: done  
• Demonstrator: tbc  
• Deployment: > 2020 onwards | • Laboratory: done  
• Pilot: 2013  
• Demonstrator: 2020  
• Deployment: > 2030  
• Other direct reduction (MIDREX is industrial) | • Laboratory: done  
• Pilot: 2011-2013TATA steel IJmuiden  
• Demonstrator: 2020  
• Deployment: > 2030  
• Other smelters (FINEX and COREX are industrial) | • Laboratory: ongoing  
• Pilot: 2020  
• Demonstrator: 2030  
• Deployment: > 2040  
• Experimental (current pilots work at ~5kg capacity per day) |
### Process changes
For each ambition level, a combination of the various technologies is proposed

#### Technology applicability along the different ambitions
(% of total steel production, (allocation available of scrap))

<table>
<thead>
<tr>
<th>Ambition</th>
<th>Oxygen steel</th>
<th>Electric steel</th>
<th>Electrolysis</th>
<th>Proportion of scrap in steel production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Classic</td>
<td>Top Gas Recycling (Hlsarna, not ULCORED)</td>
<td>Hydrogen based reduction</td>
<td>DRI EAF</td>
</tr>
<tr>
<td>1</td>
<td>✓70% (7,7% scrap)</td>
<td>✓0% (-scrap)</td>
<td>✓ -</td>
<td>✓5% (3,3% scrap)</td>
</tr>
<tr>
<td>2</td>
<td>✓61% (8,5% scrap)</td>
<td>✓2% (0,1% scrap)</td>
<td>✓ -</td>
<td>✓6% (4,2% scrap)</td>
</tr>
<tr>
<td>3</td>
<td>✓48% (9,8% scrap)</td>
<td>✓5% (0,5% scrap)</td>
<td>✓ -</td>
<td>✓8% (5,2% scrap)</td>
</tr>
<tr>
<td>4</td>
<td>✓25% (10,0%scrap)</td>
<td>✓10% (3% scrap)</td>
<td>✓ -</td>
<td>✓10% (7% scrap)</td>
</tr>
</tbody>
</table>

**NOTES:**
Assumption all scrap is used
This lever should be used jointly with the scrap availability lever, specific consumption of the various routes is tailored, assuming 100% scrap based to be 3 times less energy intensive.
To limit economic damage, classic oxygen plants are not all decommissions by 2050, and some are converted to Top gas.
Steel overcapacity context will be adverse to change and investments

**SOURCE:** Global Calculator consultation & analysis
### Process changes
For each process route, costs are applied

<table>
<thead>
<tr>
<th>Blast Oxygen furnace cost assumptions (1)</th>
<th>€/t crude steel</th>
<th>Retrofit</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>117,36</td>
<td>117,36</td>
<td></td>
</tr>
<tr>
<td>Other opex</td>
<td>371,64</td>
<td>371,64</td>
<td></td>
</tr>
<tr>
<td>Capex</td>
<td>171</td>
<td>441</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scrap based EAF cost assumptions (2)</th>
<th>€/t crude steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input (fuel &amp; material)</td>
<td>58,68</td>
</tr>
<tr>
<td>Other opex</td>
<td>430,32</td>
</tr>
<tr>
<td>Capex</td>
<td>184</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DRI based EAF cost assumptions (2)</th>
<th>€/t crude steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input (fuel &amp; material)</td>
<td>74,36</td>
</tr>
<tr>
<td>Other opex</td>
<td>497,64</td>
</tr>
<tr>
<td>Capex</td>
<td>414</td>
</tr>
</tbody>
</table>

**Source:** (1) Eurofer Steel Roadmap towards a low carbon economy 2050 (2013)

**Notes:** (2) Excluding decommissioning costs
## Process changes
Top gas/HIsarna, Electric steel and Electrolysis condition the applicability of the other levers

### Lever applicability along the main technical options

<table>
<thead>
<tr>
<th>Type of lever</th>
<th>Improvement Lever</th>
<th>Oxygen steel</th>
<th>Electric steel</th>
<th>Electrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product mix</td>
<td>Increase in higher strength steel</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Process improvement</td>
<td>Reduction of carboniferous materials (non-fuel related)</td>
<td>✓ (Sidmar close to limits)</td>
<td>✓ (already included)</td>
<td>/</td>
</tr>
<tr>
<td>Smelt reduction</td>
<td>/</td>
<td>/ (redundant with Ulcored /HIsarna)</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Alternatives</td>
<td>Coal substitution by gas injection</td>
<td>✓</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Coal substitution by biomass</td>
<td>✓</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>Reduce mechanical and thermal losses</td>
<td>✓</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>CHP potential</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>End of pipe</td>
<td>Carbon capture &amp; storage</td>
<td>✓ (less likely)</td>
<td>✓</td>
<td>/</td>
</tr>
</tbody>
</table>
Insights applicable along Process improvements, fuel substitution and energy efficiency

- The recent rapid expansion of crude steel production and the resulting additional capacity positively affected the energy efficiency of the industry (1)
- Additional capacity has reduced the average age of the capital stock, and the new plants tend to be more energy efficient, although not all have introduced BATs
- In several countries, existing furnaces have been retrofitted with energy efficient equipment, and energy efficiency policies have led to the early closure of inefficient plants
- The sector still has the technical potential to further reduce energy consumption by approximately 20% (2)
- There is a multitude of process improvements such as the Near net shape casting which can still be implemented

Source: (1) World Steel, 2011, (2) IEA ETP 2012
Comments on EAF DRI technology

• With the data used, EAF DRI has a specific consumption close to 4 times the Scrap EAF and close to the BOF
• It is to note that some sources mention that DRI enables a 20% energy consumption reduction vs BOF\(^{(1)}\)
• DRI based EAF production is expected to gain share in total crude steel production
• Assumption DRI will be used in the future unless we don’t have any more fracking
• In level 4, this will be 0% (no scrap left)

SOURCE: (1) Eurofer Steel Roadmap towards a low carbon economy 2050 (2013)
NOTES  (2) Excluding decommissioning costs
Process improvements: Top-gas recirculation/HIsarna
Proposed lever ambitions

Comments on Top-gas and HIsarna technology

- Retrofits enable a 20%\(^{(1)}\) consumption reduction
- Greenfield full HIsarna implementation are modelled, these enable a 35% consumption reduction\(^{(3)}\)
- Carbon capture is modelled by the CCS lever (not here)

NOTES
(1) Eurofer Steel Roadmap towards a low carbon economy 2050 (2013)
(2) Assuming the additional capex is balanced by the input reduction
(3) Belgian consultation
### Process improvements: Hydrogen based reduction

**Proposed lever ambitions**

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
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<td><strong>Maximum effort</strong> to reach results close to technical and physical constraints</td>
</tr>
<tr>
<td>• 0%</td>
<td>• 0%</td>
<td>• 0%</td>
<td>• 0%</td>
</tr>
</tbody>
</table>

This technology is considered a far away technology breakthrough and we therefore do not include it, even in level 4 ambition.
<table>
<thead>
<tr>
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</tr>
<tr>
<td>• 0%</td>
<td>• 0%</td>
<td>• 0%</td>
<td>• 0%</td>
</tr>
</tbody>
</table>

This technology is considered a far away breakthrough (current pilots work at ~5kg capacity per day\(^{(1)}\)) and we therefore still do not include it in level 4 ambition

**Figure of July 2014**

SOURCE: Steel consultation Wallonia Low Carbon 2050
### Fuel substitution: Coke substitution by Gas injection

#### Proposed lever ambitions

<table>
<thead>
<tr>
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<td><strong>Maximum effort</strong> to reach results close to technical and physical constraints</td>
</tr>
</tbody>
</table>

- **0% coke replaced by gas in non-Hisarna oxygen**
- **2% coke replaced by gas in non-Hisarna oxygen**
- **3% coke replaced by gas in non-Hisarna oxygen**
- **5% coke replaced by gas in non-Hisarna oxygen**

#### Lever cost

<table>
<thead>
<tr>
<th>Input (fuel &amp; material)</th>
<th>Cost of fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other opex</td>
<td>0</td>
</tr>
<tr>
<td>Capex</td>
<td>0</td>
</tr>
</tbody>
</table>

**SOURCE:** Steel consultation Wallonia Low Carbon 2050
## Fuel substitution: Coal substitution by biomass
### Proposed lever ambitions

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Moderate effort easily reached according to most experts</td>
<td>Significant effort requiring cultural change and/or important financial investments</td>
<td>Maximum effort to reach results close to technical and physical constraints</td>
</tr>
</tbody>
</table>

- / 
- Substitution of 15% coal PCI by biomass in non Hisarna oxygen
- idem level 2
- idem level 2

**Lever cost**

<table>
<thead>
<tr>
<th>Input (fuel &amp; material)</th>
<th>Cost of fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other opex</td>
<td>0</td>
</tr>
<tr>
<td>Capex</td>
<td>0</td>
</tr>
</tbody>
</table>

This technology has limited impact after Hisarna
Energy (and material) efficiency
Energy efficiency has drastically improved over the last 30 years, leaving limited improvement on existing technology.

Energy intensity (1) (2)
(GJ/ton crude steel)

- With strong historical improvement in energy efficiency, we assume limited further improvement (with same technologies)
- There is ~25% scrap through the chain which can be reused (this is accounted through additional scrap availability in level 4 and not here)
- Downstream processes also reveal significant improvement potential; In the EU, through downstream improvements, total energy efficiency could be improved by 5% \(^{(4)}\)
- However, replacing all existing plants by BaT will enable a certain reduction
- Efficiency improvements are only applied on non-Hisarna BOF

Lever cost \(^{(3)}\) €/t crude steel

<table>
<thead>
<tr>
<th>Input (fuel &amp; material)</th>
<th>-x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other opex</td>
<td>0</td>
</tr>
<tr>
<td>Capex (Assuming 5 years payback on energy savings)</td>
<td>127 +x</td>
</tr>
</tbody>
</table>
### Energy efficiency: CHP potential

#### Proposed lever ambitions

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
</table>
| **Minimum effort**  
(following current regulation) | **Moderate effort**  
easily reached according to most experts | **Significant effort**  
requiring cultural change and/or important financial investments | **Maximum effort**  
to reach results close to technical and physical constraints |

- **Level 1**
  - No additional potential

- **Level 2**
  - No additional potential

- **Level 3**
  - No additional potential

- **Level 4**
  - No additional potential

---

No potential remains after all energy efficiency measures have been implemented

---

**Note:** (1) Includes the behavioural, the energy audits.
Capture rate
(MtCO₂/year)

SOURCE: IEA ETP 2012
Typical ranges of costs of emission reductions from industrial applications of CCS (USD/tCO$_2$e avoided)

In addition, an electricity consumption of 0.33 TWh/MtCO$_2$e captured is modelled.

NOTE: The range of costs shown here reflect the regional average costs of applying CCS in each sector, and, therefore, the overall cost of abatement in a sector will be affected by the assumed level of CCS uptake in each sector (IEA, 2009 and IEA and UNIDO 2011). These costs include the cost of capture, transport and storage, but do not assume that storage generates revenues (i.e. CO$_2$ storage through enhanced oil recovery (EOR) is not considered as a storage option).

SOURCE: ETP 2012, IEA
**Carbon Capture & Storage**

**Proposed lever ambitions**

---

**Penetration of CCS**

(% of plants equipped)

- **Ambition 1**: 0%
- **Ambition 2**: 25%
- **Ambition 3**: 45%
- **Ambition 4**: 100%

---

**Lever cost**

<table>
<thead>
<tr>
<th>Input (fuel &amp; material)</th>
<th>0.33 TWh Elec/Mt captured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other opex</td>
<td>$20 USD/ton captured</td>
</tr>
<tr>
<td>Capex</td>
<td>$40 USD/ton captured</td>
</tr>
</tbody>
</table>

---


---

**Figures of July 2014**

- Several pilots available but industrial scale not rolled out before 2030
- Could be cheaper than top-gas recycling to reduce emissions (2)
- Ambition 3 aligned to ETP 2012 ambition of 40-45% plants
- 80% capture rate (1)
- Only applied on oxygen steel & DRI in levels 1,2,3 & 4
- The specificities of CCS in the steel sector (e.g. energy consumption) should be refined in a later version of the model
Model growth forecasts
Production according to trajectories 1, 2 and 3
(after design, switch & recycling)

Steel production per year per ambition (1,2) (M tons)

<table>
<thead>
<tr>
<th>Year</th>
<th>Trajectory 1</th>
<th>Trajectory 2</th>
<th>Trajectory 3</th>
<th>Trajectory 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>1,000</td>
<td>800</td>
<td>700</td>
<td>800</td>
</tr>
<tr>
<td>2015</td>
<td>2,000</td>
<td>1,600</td>
<td>1,400</td>
<td>1,600</td>
</tr>
<tr>
<td>2020</td>
<td>3,000</td>
<td>2,400</td>
<td>2,100</td>
<td>2,400</td>
</tr>
<tr>
<td>2025</td>
<td>3,500</td>
<td>2,700</td>
<td>2,500</td>
<td>2,700</td>
</tr>
<tr>
<td>2030</td>
<td>4,000</td>
<td>3,000</td>
<td>2,800</td>
<td>3,000</td>
</tr>
<tr>
<td>2035</td>
<td>4,500</td>
<td>3,300</td>
<td>3,100</td>
<td>3,300</td>
</tr>
<tr>
<td>2040</td>
<td>5,000</td>
<td>3,600</td>
<td>3,400</td>
<td>3,600</td>
</tr>
<tr>
<td>2045</td>
<td>5,500</td>
<td>3,900</td>
<td>3,600</td>
<td>3,900</td>
</tr>
<tr>
<td>2050</td>
<td>6,000</td>
<td>4,200</td>
<td>3,900</td>
<td>4,200</td>
</tr>
</tbody>
</table>

Delta 10-50,%

- Trajectory 1: +124%
- Trajectory 2: +72%
- Trajectory 3: +39%
- Trajectory 4: +9%

Implied demand per person

- Trajectory 1: 355 kg steel/person
- Trajectory 2: 273 kg steel/person
- Trajectory 3: 221 kg steel/person
- Trajectory 4: 174 kg steel/person

NOTE:
(1) The population follows the average UN projection in all four trajectories
(2) Other sectors are impacted by these transitions (e.g. additional productions are created in the aluminium and plastics sectors)

SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Details for ambition level 3\(^{(1)}\)

Steel production for ambition level 3
(M tons, % of 2011)

Trajectories\(^{(1)}\) in 2050

NOTE:
(1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions

SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Emissions according to different trajectories

GHG emissions for different ambition levels (1,2,3) (MtonCO$_2$e)

### Delta 10-50,% Specific emissions

- **1** +123% 2,0 tCO$_2$e /tsteel
- **2** +35% 1,6 tCO$_2$e /tsteel
- **3** -6% 1,3 tCO$_2$e /tsteel
- **4** -84% 0,3 tCO$_2$e /tsteel

**NOTE:**
(1) The population follows the average UN projection in all four trajectories
(2) Excluding biomass related reductions & electricity related emissions
(3) Other sectors are impacted by these transitions (e.g. additional emissions are created in the aluminium and plastics sectors)

SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Details for ambition level 3

Steel GHG emissions in 2050, for ambition level 3\(^{(1,2)}\), using different levers\(^{(3)}\)
(MtCO\(_2\)e, % of 2010)

NOTES:
(1) The population follows the average UN projection in all four trajectories
(2) Excluding biomass related reductions & electricity related emissions
(3) Other sectors are impacted by these transitions (e.g. additional emissions are created in the aluminium and plastics sectors)
Percentage reductions are calculated vs the 2010 baseline

SOURCE: IEA ETP 2012, Global calculator model
Cost
Marginal cost and abatement potential for different levers under trajectory 2 with ambition level 4

GHG abatement curve for the year 2050 (trajectory 2, ambition 4)
€/tCO₂e, % emission abatement in 2050 (% of 2010 level)

NOTE: Hypothesis of cost neutral energy efficiency measures, cost of biomass generic across all sectors
SOURCE: Global calculator model
2050 evolution of materials and emissions

Materials demand evolution
  • Cross sector demand
  • Cross sector material switch
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper & Timber

Reduction potential on the manufacturing processes
  • Resulting emissions
  • Discussion on ambition levels across sectors
  • Discussion on CCS
  • Steel
  • **Chemicals**
    • Aluminium
    • Cement
    • Paper, Timber & Other
130 different industrial processes are used to manufacture the largest 18 volume chemicals, however 4 chemicals families are being assessed.

**NOTE**: (1) Ethylene, Propylene, BTX aromatics (benzene, toluene and mixed xylenes)

SOURCE: Climact
4 chemicals families are being assessed

Technology

Ammonia

Feed
CH₄, H₂O

- Reformer

CO₂

Syngas (H₂ & CO)

- CO shift converter

H₂+CO₂

- Acid gas removal

CO₂

H₂

N₂

Ammonia

NH₃

Methanol

Feed
CH₄, H₂O

- Reformer

H₂, CO, CO₂

- Converter

H₂O, CH₃OH, H₂, CO, CO₂

- Methanol separator

H₂O, CH₃OH,

- Distillation

H₂, CO₂, CO

H₂O

Methanol

CH₃OH

NOTE: Haber-Bosch process
SOURCE: ICCA Catalytic roadmap
Chemicals emissions are being modelled

Chemicals emission tree

- **Chemicals**
  - **High Value Chemicals**
    - Production
    - Energy Intensity
    - Process intensity
  - **Ammonia**
    - Production
    - Energy Intensity
    - Process intensity
  - **Methanol**
    - Production
    - Energy Intensity
    - Process intensity
  - **Other chemicals**
    - Production
    - Energy Intensity
    - Process intensity

SOURCES: Climact
### Order and applicability of levers per chemical family

<table>
<thead>
<tr>
<th>Lever</th>
<th>HVC</th>
<th>Ammonia</th>
<th>Methanol</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material switch</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Green plastics</td>
<td>✔</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Products recycling</td>
<td>✔</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Materials recycling</td>
<td>✔</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Improved design</td>
<td>✔</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Process changes</td>
<td>✔ Catalytic naphta cracking</td>
<td>✔ Hydrogen production</td>
<td>✔ Hydrogen production</td>
<td>/</td>
</tr>
<tr>
<td>Fuel switches</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>CCS</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>
List of actions & levers assessed

**Design**
- Changing product and material specifications to answer the same needs with less materials

**Switch**
- Change materials to enable a low carbon product (over the product lifetime)

**Recycling**
- Recycle the product or the material

**Smart design**
- In buildings/Infr.: To bio-based plastics & to timber

**Product recycling**

**Material recycling**

**Bio-based plastics**

**CCU discussion**

SOURCE: Climact
Product mix: Improved design
Chemicals recycling rates are much lower than in other industries

Reduced material demand through improved design (%)

Rationale

- Improved composites and polymers will have significantly better properties
- Production of plastics leads to limited yield loss (some moulding enable no loss at all)

SOURCE: (1) With both eyes open
Product mix: Material switch
Steel is a relatively cheap material

- Compared to other materials, plastics have relatively high embedded energy and useful costs
- If plastics substitutes other materials, it will be for its ease of mouldability or characteristics during product life

Embodied energy to convert the material in useful form

Relative cost per tonne to convert the materials in useful form

NOTE: (1) Refer to “With both eyes open” for more details on the definition of useful costs
SOURCE: (1) With both eyes open
Large scale adoption of carbon fibre is hindered by high costs

Carbon fibre market evolution
(Million pounds)

SOURCE: Deutsche Bank; expert interviews; Zoltek; McKinsey Global Institute analysis
## Chemicals

Chemicals can substitute other materials if they enable lower emissions during the whole product life cycle.

### Materials which can replace /be replaced by chemicals

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Advantages</th>
<th>Weaknesses</th>
<th>Chemicals replacement assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>HVC</td>
</tr>
<tr>
<td><strong>Aluminium</strong></td>
<td>Recyclability</td>
<td>Density</td>
<td>Not modelled</td>
</tr>
<tr>
<td></td>
<td>Lower cost &amp; embodied energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Steel</strong></td>
<td>Recyclability</td>
<td>Density</td>
<td>Corrosion</td>
</tr>
<tr>
<td></td>
<td>Lower cost &amp; embodied energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Concrete</strong></td>
<td>“Recyclability”, Low cost &amp; embodied energy, no corrosion</td>
<td>Weak in tension</td>
<td>Insulation materials substitutes cement in buildings/infrastructure(1)</td>
</tr>
<tr>
<td><strong>Stone &amp; Masonry</strong></td>
<td>Lower embodied emissions</td>
<td>Must be reinforced with mortar. Cannot be reinforced or moulded</td>
<td>Not modelled</td>
</tr>
<tr>
<td><strong>Biomass (Timber/paper)</strong></td>
<td>high strength and stiffness per density(1)</td>
<td>Less durable, sensitive to fire and rot, less stable</td>
<td>Not modelled (1)</td>
</tr>
</tbody>
</table>

**NOTES:**
1. Development of mega cities increases demand for noise and heat insulation products. Performance will take a larger role (e.g. to gain space)
2. Green chemistry is modelled in another lever
3. 15% of plastics in cars today. With trend towards EV, there will be more emphasis on the need for light weight materials
## Product mix: Material switch

### Proposed lever ambitions

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minimum effort</strong> (following current regulation)</td>
<td><strong>Moderate effort</strong> easily reached according to most experts</td>
<td><strong>Significant effort</strong> requiring cultural change and/or important financial investments</td>
<td><strong>Maximum effort</strong> to reach results close to technical and physical constraints</td>
</tr>
</tbody>
</table>

**Vehicles:**
- 0% switch

**Buildings:**
- 0% switch

<table>
<thead>
<tr>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
</table>
| **Vehicles**
  - 5% steel $\rightarrow$ plastics
  - **Buildings/Infra:**
    - 5% cement $\rightarrow$ green plastics | **Vehicles**
  - 10% steel $\rightarrow$ plastics
  - **Buildings/Infra:**
    - 10% cement $\rightarrow$ green plastics | **Vehicles**
  - 20% steel $\rightarrow$ plastics
  - **Buildings/Infra:**
    - 20% cement $\rightarrow$ green plastics |

### Lever cost ($€/t$ chemicals)

<table>
<thead>
<tr>
<th>Material switch</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel $\rightarrow$ Plastics</td>
<td>0</td>
</tr>
<tr>
<td>Concrete $\rightarrow$ Plastics</td>
<td>153</td>
</tr>
</tbody>
</table>

**NOTE:**
1. Amount of one material required to replace another material is approximated through the specific Young modulus
2. Assumption this material switch does not impact the product life

Figures of July 2014
NOTES: Biomass availability is constrained, and enters in competition with biomass use for food, other products and energy.
The Global calculator illustrates the impacts of using biomass
Some estimates lead to 10% of biomass in feedstock, (these figures include a wider scope e.g. biofuels and waste from slaughter houses)
SOURCE: (1) Fost+ environmental impact of biopackaging
Product mix: Green plastics (2/4)
Using biomass feedstock can be significantly more energy intensive than the established fossil-based routes

Energy use for biomass versus fossil routes to HVC (GJ/t HVC)

- The previous slides notes the competition for biomass. Likewise, there is competition for fossil fuels (between energy and product applications)
- This model does not look at the subsidies dimension, it is worth noting however that there are currently no subsidies planned for sequestering CO₂ in products (e.g. ETS only looks at emissions)

NOTE: EtOH = Ethanol
SOURCE: (1) DECHEMA
Product mix: Green plastics (3/4)

Only a small proportion of plastics can be made from biomass

Share of green plastics within HVC (%)

Rationale on green plastics rates

- Several monomers, such as the ethylene olefins, can be produced from plants (e.g. sugar cane)\(^{(2)}\)
- More generally the feedstock can be made from biomass
- Bioplastics also tend to be more biodegradable than oil based plastics (but all 4 combinations are possible)
- Overall, the energy consumption of the relevant biomass routes is 3.5 to 5 times that of the fossil route \(^{(2)}\). We assume it requires no more fossil energy
- Catalysis process changes (lever addressed later) facilitate the inclusion of biomass feedstock

NOTE: \(^{(2)}\) The largest commercial activity currently takes place in Brazil, where the Brazilian petrochemical company Braskem operates the first industrial-scale sugarcane-based ethanol plant (200 kt/yr capacity) for subsequent polyethylene production.

SOURCE: (1) With both eyes open (2) ICCA
Product mix: Green plastics (4/4)
Caveat on modelling

CCU was not modelled at significant scale in this version of the tool

- For higher rates of Carbon Capture & Usage (CCU), the development of a hydrogen supply chain was required
- Hydrogen supply chain has since been modelled in industry in the second version of the calculator
Global Calculator

Design will evolve to make products more recyclable.

Product recycling is difficult because of the large amount of different plastic applications, and the cheap price of plastics.

2 application areas are identified:

- Packaging in the UK
  - ~20kg packaging/person/year is in the end consumer waste
  - ~30kg packaging/person/year is for moving goods from factory to factory or shops
  - There is a potential to further recycle packaging products, especially the reuse of industrial packaging
- Construction
  - Pipes could be dismantled and reused
  - Car components could be reused

Rationale on product recycling

Recycling share (%)

Ambition 1 (2.5%)
Ambition 2 (5%)
Ambition 3 (7.5%)
Ambition 4 (10%)

~% based on 0

2000 2010 2020 2030 2040 2050

Lever cost (€/t chemicals)

0 (also generates value)

NOTE: (1) Only applied to non biodegradable plastics
Rationale on plastics recycling rates

- Low plastics value and higher recycling complexity make plastic recycling less attractive
- Higher complexity comes from:
  - the higher variability of plastic manufacturing processes and additives (to change colours & properties) & fillers (cheaper materials which increase strength & hardness)
  - The fact plastics are harder to isolate from other waste streams (e.g. it is weakly magnetic)
- Only thermoplastics can be recycled (not the thermosets) (2)

Solutions

- Production scraps can easily be recycled (not much improvement potential is expected here)
- Improved separation of plastics waste streams from municipal waste (difficult because diverse)
- Improved sorting of plastics waste stream (difficult because similar density and optical properties)
- There are 4 levels of recycling:
  - Primary recycling: material is directly reextruded
  - Secondary recycling: plastics is ground in small chips, washed, dried & converted in resins (lower quality)
  - Tertiary recycling: plastics are broken down chemically to produce new feedstock (e.g. by pyrolysis)
  - Quaternary recycling: recovery of energy through incineration (this is addressed in the supply/waste analysis, not in manufacturing)

NOTE: (2) There are 2 families of plastics A) Thermoplastics which represent most of the plastics. These can be melted and reformed several times. B) Thermosets, which represent a smaller portion of the plastics. These change irreversibly on being heated, mixed, irradiated, and cannot be recycled (e.g. glass & carbon fibers)

SOURCE: (1) With both eyes open
Product mix: Materials recycling
A higher proportion of plastics can be made from these 4 recycling levels

Recycling share (%)

Ambition 1 (5%)  
Ambition 2 (10%)  
Ambition 3 (15%)  
Ambition 4 (20%)

Simplifying assumption: applied to all chemicals, even though ammonia fertilizers will not have recycling potential

Lever cost (€/t chemicals)
0 (also generates value)

SOURCE: (1) With both eyes open
Carbon intensity of material production
The chemical sector has significantly improved historically but major improvements are still available

Historical improvements

The sector has recently strongly improved its energy efficiency

For example, in the US, energy intensity of the chemical sector improved by 39% and GHG emissions intensity was reduced by 10% between 1994 and 2007 (1)

Remaining improvement levers

Various levers are available:
- Better heat integration
- Catalyst tweaks
- State-of-the-art equipment
- Better catalysts
- Separations
- …

SOURCE: (1)ICCA catalytic roadmap
Carbon intensity of material production
Process improvements, fuel mixes, energy efficiency & CCS are then assessed

List of actions & levers assessed

**Process improvement**
- Towards fuels which emit less CO₂

**Fuel substitution**
- Modification of processes

**Energy efficiency**
- Reduce mechanical and thermal losses
- Recuperate thermal energy (CHP)

**End of pipe technologies**
- Carbon capture and storage

- Various
- Biomass
- Waste
- Insulation
- CHP/heat recovery
- Various
- CCS implementation

NOTE: Process choice has consequences on applicability of other levers. Some combinations are exclusive whilst others can be added in sequential order.

SOURCE: (1) (redundant with Ulcored while we represent Hlsarna in this analysis)
### Process improvement examples

<table>
<thead>
<tr>
<th>High value chemicals</th>
<th>Process improvement examples</th>
<th>Energy savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olefin production via catalytic cracking of naphtha and via methanol, moving away from steam cracking</td>
<td>Could deliver energy savings of 10% to 20% (2)</td>
<td></td>
</tr>
<tr>
<td>Olefin production via methanol</td>
<td></td>
<td>Not modelled, we simplify assuming all HVC switch to the catalytic process</td>
</tr>
<tr>
<td>Propylene Oxide (PO)production via the hydrogen peroxide propylene oxide (HPPO) process</td>
<td>Could deliver energy savings of 10-12% (1), but is not modelled cfr supra</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ammonia</th>
<th>Hydrogen based production of ammonia</th>
<th>+26 GJ/ t ammonia (NH₃) Vector switch to 100% electricity</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Methanol</th>
<th>Hydrogen based production of methanol</th>
<th>+15.7 GJ/ t methanol (NH₃) Vector switch to 100% electricity</th>
</tr>
</thead>
</table>

| Other chemicals      | Improved hydrogen generation for steam methane reformers                                                             |                                                                           |
|----------------------|--------------------------------------------------------------------------------------------------------------------|                                                                           |
|                      | Synthesis of aromatics from lignin, ethanol or methane                                                              |                                                                           |
|                      | Direct synthesis of hydrogen peroxide from hydrogen and oxygen                                                      |                                                                           |
|                      | Direct epoxidation of propylene with oxygen                                                                         |                                                                           |

SOURCE: (1)ICCA Catalytic roadmap (2) Ren, Patel and Blok, 2006
Additional energy demand versus fossil energy savings for replacement of current ammonia and methanol processes by hydrogen-based routes

(% implementation of hydrogen route)

- Ammonia synthesis based on hydrogen from renewable energy sources requires roughly 26 GJ/t ammonia (NH₃) more energy (and we assume a vector switch to electricity)
- For methanol (MeOH) from hydrogen and coal, an additional 15.7 GJ/tMeOH are required compared to the gas steam reforming route and additional 5.6 GJ/tMeOH compared to the coal partial oxidation route (and we assume a vector switch to electricity)

SOURCE: (1) DECHEMA, ICCA catalytic roadmap
Process improvements
Production of hydrogen from renewables currently uses a lot of energy

Chosen ambition levers

<table>
<thead>
<tr>
<th>Process description</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High value chemicals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Olefin production via naphtha catalytic cracking</td>
<td>0%</td>
<td>-5%</td>
<td>-10%</td>
<td>-20%</td>
<td>Reduction of specific consumption (1)</td>
</tr>
<tr>
<td>• Olefin production via methanol</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>• Propylene Oxide (PO) production via (HPPO) process</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>Benefits related to the application of HPPO are included in the above reduction</td>
</tr>
<tr>
<td><strong>Ammonia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Hydrogen based production of ammonia</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>30%</td>
<td>% switch to new technology +26 GJ/ t ammonia (NH3) Vector switch to 100% electricity</td>
</tr>
<tr>
<td><strong>Methanol</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Hydrogen based production of methanol</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>30%</td>
<td>% switch to new technology +15.7 GJ/ t methanol (NH3) Vector switch to 100% electricity</td>
</tr>
<tr>
<td><strong>Other chemicals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Improved hydrogen generation for steam methane reformers</td>
<td>0%</td>
<td>-5%</td>
<td>-10%</td>
<td>-20%</td>
<td>Assuming same evolution as HVC</td>
</tr>
<tr>
<td>• Synthesis of aromatics from lignin, ethanol or methane</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Direct synthesis of hydrogen peroxide from hydrogen and oxygen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Direct epoxidation of propylene with oxygen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: (1) this is not based on coal, that would increase emissions
SOURCE: (1) DECHEMA, ICCA catalytic roadmap

Lever cost (1)

<table>
<thead>
<tr>
<th>Input (fuel &amp; material)</th>
<th>Fuel costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other opex</td>
<td>166</td>
</tr>
<tr>
<td>Capex</td>
<td>0</td>
</tr>
</tbody>
</table>
### Fuel switches

A significant portion of fuels (excl. feedstock) can be switched to biomass

#### Chosen ambition levers

<table>
<thead>
<tr>
<th>Switch description</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High value chemicals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Solid &amp; liquid to gaseous</td>
<td>0%</td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
<td>Same specific consumption</td>
</tr>
<tr>
<td>- Solid &amp; gaseous hydrocarbons to biomass (2)</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
<td>20%</td>
<td>Specific consumption of biomass 5% higher</td>
</tr>
<tr>
<td><strong>Ammonia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Solid hydrocarbons to biomass (2)</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
<td>20%</td>
<td>Specific consumption of biomass 5% higher</td>
</tr>
<tr>
<td><strong>Methanol</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Solid hydrocarbons to biomass (2)</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
<td>20%</td>
<td>Specific consumption of biomass 5% higher</td>
</tr>
<tr>
<td><strong>Other chemicals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Solid hydrocarbons to biomass (2)</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
<td>20%</td>
<td>Specific consumption of biomass 5% higher</td>
</tr>
</tbody>
</table>

#### Lever cost (1)

<table>
<thead>
<tr>
<th>Input (fuel &amp; material)</th>
<th>Fuel costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other opex</td>
<td>167</td>
</tr>
<tr>
<td>Capex</td>
<td>0</td>
</tr>
</tbody>
</table>

**NOTE:** (2) Not related to feedstock (addressed in green plastics lever)

**SOURCE:** (1) Climact

**Global Calculator**

Figures of July 2014
# CHP

Up to 20% of the sector electricity can be covered by Combined heat and power units

## Chosen ambition levers

<table>
<thead>
<tr>
<th>Level description</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Modelling</th>
</tr>
</thead>
</table>
| **High value chemica ls** | • % of the electricity consumption covered by the CHP | 5% | 10% | 15% | 20% | • In this 1st version of the tool, it is approximated by x kwh of electricity which can be replaced by x kwh of gas  
• This covers the autoproducers  
• This does not cover the large CHP units which are classified as Electricity producers |
| **Ammonia** | • % of the electricity consumption covered by the CHP | 5% | 10% | 15% | 20% | |
| **Methanol** | • % of the electricity consumption covered by the CHP | 5% | 10% | 15% | 20% | |
| **Other chemica ls** | • % of the electricity consumption covered by the CHP | 5% | 10% | 15% | 20% | |

### Lever cost *(1)*

<table>
<thead>
<tr>
<th>Input (fuel &amp; material)</th>
<th>Fuel costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other opex</td>
<td>168</td>
</tr>
<tr>
<td>Capex</td>
<td>0</td>
</tr>
</tbody>
</table>

**NOTE:** (2) Not related to feedstock (addressed in green plastics lever)  
SOURCE: (1) Climact high level assumption
### Energy efficiency rationale (in addition to the technology modifications addressed earlier)

<table>
<thead>
<tr>
<th>High value chemicals</th>
<th>• Could deliver energy savings ~20% in addition to the process change (^{(2)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>• Applied on the part not switching to hydrogen based production</td>
</tr>
<tr>
<td></td>
<td>• Stochiometric: 19.8 GJ/t NH(_3)  (\text{BAT 2050: 24 GJ/t NH}_3) (^{(3)})</td>
</tr>
<tr>
<td></td>
<td>• Standard technology 39 GJ/t NH(_3) - new BAT technology 28 GJ/t NH(_3) (-30%)(^{(1)})</td>
</tr>
<tr>
<td></td>
<td>• Retrofit options for improvements of reformer section and CO(_2) removal section</td>
</tr>
<tr>
<td></td>
<td>• Potential for low pressure (improved catalysts) and improved process control</td>
</tr>
<tr>
<td>Methanol</td>
<td>• Applied on the part not switching to hydrogen based production</td>
</tr>
<tr>
<td></td>
<td>• Assumption same as ammonia</td>
</tr>
<tr>
<td>Other chemicals</td>
<td>• Assumption same as HVC</td>
</tr>
</tbody>
</table>

**NOTE:** Not related to feedstock (addressed in green plastics lever)

**SOURCE:**
1. Source: SERPEC study
2. ICCA Catalytic roadmap
3. Source: VITO analysis
## Energy efficiency improvements

<table>
<thead>
<tr>
<th>Description</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High value chemicals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Specific consumption reduction</td>
</tr>
<tr>
<td>Newer plants &amp; retrofits</td>
<td>0%</td>
<td>-5%</td>
<td>-10%</td>
<td>-20%</td>
<td></td>
</tr>
<tr>
<td><strong>Ammonia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Specific consumption reduction</td>
</tr>
<tr>
<td>Newer plants &amp; retrofits</td>
<td>0%</td>
<td>-7.5%</td>
<td>-15%</td>
<td>-30%</td>
<td></td>
</tr>
<tr>
<td><strong>Methanol</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Specific consumption reduction</td>
</tr>
<tr>
<td>Newer plants &amp; retrofits</td>
<td>0%</td>
<td>-7.5%</td>
<td>-15%</td>
<td>-30%</td>
<td></td>
</tr>
<tr>
<td><strong>Other chemicals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Specific consumption reduction</td>
</tr>
<tr>
<td>Newer plants &amp; retrofits</td>
<td>0%</td>
<td>-5%</td>
<td>-10%</td>
<td>-20%</td>
<td></td>
</tr>
</tbody>
</table>

### Lever cost

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input (fuel &amp; material)</td>
<td>-X</td>
</tr>
<tr>
<td>Other opex</td>
<td>0</td>
</tr>
<tr>
<td>Capex</td>
<td>170</td>
</tr>
</tbody>
</table>

**SOURCE:** (2) Climact assumption
Capture rate
(MtCO₂/year)

SOURCE: IEA ETP 2012
Typical ranges of costs of emission reductions from industrial applications of CCS (USD/tCO₂e avoided)

In addition, an electricity consumption of 0.33 TWh/MtCO₂e captured is modelled

NOTE: The range of costs shown here reflect the regional average costs of applying CCS in each sector, and, therefore, the overall cost of abatement in a sector will be affected by the assumed level of CCS uptake in each sector (IEA, 2009 and IEA and UNIDO 2011). These costs include the cost of capture, transport and storage, but do not assume that storage generates revenues (i.e. CO₂ storage through enhanced oil recovery (EOR) is not considered as a storage option.

SOURCE: ETP 2012, IEA
Carbon Capture & Storage
Proposed lever ambitions

Penetration of CCS
(% of plants equipped)

- Large facilities for the production of ammonia, methanol, ethylene oxide, hydrogen and products from coal gasification might have sufficient scale to make CCS financially feasible.
- Crackers can also be high-volume sources (1 MtCO₂/yr), but their flue gas is more dilute (4% to 7% CO₂, lower concentration than a coal-fired power plant which can be 10% CO₂ to 12% CO₂) and drive up the CO₂ capture costs.
- IEA 2DS suggest a capture of 467MtCO₂ for the chemical sector.
- 80% capture rate (1)
- The specificities of CCS in the steel sector (e.g. energy consumption) should be refined in a later version of the model.

Lever cost (2)

<table>
<thead>
<tr>
<th>Input (fuel &amp; material)</th>
<th>0.33 TWh Elec/Mt captured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other opex</td>
<td>$20 USD/ton captured</td>
</tr>
<tr>
<td>Capex</td>
<td>$40 USD/ton captured</td>
</tr>
</tbody>
</table>

SOURCE: (1) IEA ETP 2012
Model growth forecasts
Production according to trajectories 1, 2 and 3 (after design, switch & recycling)

Chemicals production per year for different ambition levels

<table>
<thead>
<tr>
<th>Trajectory 1</th>
<th>Delta 10-50%,</th>
<th>Implied demand per person</th>
</tr>
</thead>
<tbody>
<tr>
<td>+118%</td>
<td>171 kg plastics/person</td>
<td></td>
</tr>
<tr>
<td>Trajectory 2</td>
<td>+46%</td>
<td>114 kg plastics/person</td>
</tr>
<tr>
<td>Trajectory 3</td>
<td>+12%</td>
<td>88 kg plastics/person</td>
</tr>
<tr>
<td>Trajectory 4</td>
<td>-16%</td>
<td>66 kg plastics/person</td>
</tr>
</tbody>
</table>

**Notes:**
1. The population follows the average UN projection in all four trajectories
2. Other sectors are impacted by these transitions (e.g. additional productions are created in the timber sector)

**Source:** IEA ETP 2012, Global calculator model
Reduction potential
Details for ambition level 3

Chemicals production for ambition level 3
(M tons, % of 2011)

Trajectories(1) in 2050

NOTE:  
(1) The population follows the average UN projection in all four trajectories  
(2) Assuming biomass emits, not including electricity related emissions

SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Emissions according to different trajectories

**GHG emissions for different ambition levels** \(^{(1,2,3)}\)
(MtonCO\(_2\)e)

<table>
<thead>
<tr>
<th>Year</th>
<th>Delta 10-50,%</th>
<th>Specific emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+118%</td>
<td>1732 kg /ton plastics</td>
</tr>
<tr>
<td>2</td>
<td>+8%</td>
<td>1287 kg /ton plastics</td>
</tr>
<tr>
<td>3</td>
<td>-64%</td>
<td>558 kg /ton plastics</td>
</tr>
<tr>
<td>4</td>
<td>-86%</td>
<td>381 kg /ton plastics</td>
</tr>
</tbody>
</table>

**NOTES:**
1. The population follows the average UN projection in all four trajectories
2. Excluding biomass related reductions & electricity related emissions
3. Other sectors are impacted by these transitions (e.g. with product switch)

**SOURCE:** IEA ETP 2012, Global calculator model
Reduction potential
Details for ambition level 3 (1)

Chemicals GHG emissions in 2050, for ambition level 3 \(^{(1,2)}\), using different levers \(^{(3)}\)
(MtCO\(_2\)e, % of 2010)

NOTES:
(1) The population follows the average UN projection in all four trajectories
(2) Excluding biomass related reductions & electricity related emissions
(3) Other sectors are impacted by these transitions (e.g. additional emissions are created in the aluminium and plastics sectors)
Percentage reductions are calculated vs the 2010 baseline
SOURCE: IEA ETP 2012, Global calculator model
Cost
Marginal cost and abatement potential for different levers under trajectory 2 with ambition level 4

GHG abatement curve for the year 2050 (trajectory 2, ambition 4)
€/tCO$_2$e, % emission abatement in 2050 (% of 2010 level)

NOTE: Hypothesis of cost neutral energy efficiency measures, cost of biomass generic across all sectors
SOURCE: IEA ETP 2012, Global calculator model
2050 evolution of materials and emissions

Materials demand evolution
  • Cross sector demand
  • Cross sector material switch
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper & Timber

Reduction potential on the manufacturing processes
  • Resulting emissions
  • Discussion on ambition levels across sectors
  • Discussion on CCS
  • Steel
  • Chemicals

  • Aluminium
    • Cement
    • Paper, Timber & Other
## Aluminium assumptions summary

<table>
<thead>
<tr>
<th>Lever</th>
<th>Ambitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>0%</td>
</tr>
<tr>
<td>Switch to Aluminium from steel</td>
<td>0%</td>
</tr>
<tr>
<td>Switch to plastics from aluminium (planes)</td>
<td>not modeled</td>
</tr>
<tr>
<td>Recycling (% of total)</td>
<td>+10%</td>
</tr>
<tr>
<td>Process improvements (as EE)</td>
<td>0%</td>
</tr>
<tr>
<td>Fuel switches (coal to biomass in primary alu)</td>
<td>0%</td>
</tr>
<tr>
<td>CHP</td>
<td>0%</td>
</tr>
<tr>
<td>Energy efficiency (additional)</td>
<td>0%</td>
</tr>
<tr>
<td>CCS (emissions captured)</td>
<td>0%</td>
</tr>
</tbody>
</table>

**NOTE:** Because it is used in long term products (aluminium locked in buildings & cables) aluminium scrap availability is expected to decrease, limiting the recycling potential.

**SOURCE:** Global Calculator consultations, World Aluminium

Figures of July 2014
Reduction potential
Details for ambition level 3

Aluminium production for ambition level 3
(M tons, % of 2011)

*NOTE:* (1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions

SOURCE: IEA ETP 2012, Global calculator model

Trajectories(1) in 2050

- Because it is used in long term products (aluminium locked in buildings & cables) aluminium recyclability rates are expected to decrease
- Current 30%, Ambition 1: 10%, 2:15% 3: 20%, 4:25%

Figures of July 2014
Reduction potential
Details for ambition level 3 (1)

Aluminium GHG emissions in 2050, for ambition level 3(1,2), using different levers(3)
(MtCO$_2$e, % of 2010)

NOTES: (1) The population follows the average UN projection in all four trajectories
(2) Excluding biomass related reductions & electricity related emissions
(3) Other sectors are impacted by these transitions (e.g. additional emissions are created in the aluminium and plastics sectors)
Percentage reductions are calculated vs the 2010 baseline
SOURCE: IEA ETP 2012, Global calculator model
2050 evolution of materials and emissions

Materials demand evolution
  • Cross sector demand
  • Cross sector material switch
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper & Timber

Reduction potential on the manufacturing processes
  • Resulting emissions
  • Discussion on ambition levels across sectors
  • Discussion on CCS
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper, Timber & Other
### Manufacturing chain definition for each technology

<table>
<thead>
<tr>
<th>Technology</th>
<th>Raw materials extraction &amp; grinding</th>
<th>Preheating, precalcining, heating &amp; cooling</th>
<th>Blinding and grinding (for cement)</th>
<th>Mixing (for concrete)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grey clinker</td>
<td>- Dry process</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CaCO₃ Limestone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SiO₂ Silica, Al₂O₃ Alumina, Fe₂O₃ Iron oxyde Clay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Powders</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Substitutes (e.g. sand)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuels</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clinker</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gypsum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other additions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White clinker</td>
<td>Idem but no iron intake</td>
<td>Idem</td>
<td>Idem but drying in a longer rotary kiln</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** The cement typically represents 10-15% of the concrete mix, is then used with water and aggregates (sand & crushed stones)

**SOURCE:** Climact analysis
Cement manufacture at a glance

Cement is a man-made powder that, when mixed with water and aggregates, produces concrete. The cement-making process can be divided into two basic steps:

1. Clinker is made in the kiln at temperatures of 1,450°C
2. Clinker is then ground with other minerals to produce the powder we know as cement
Detailed emission tree
(not modelled, but used to assess the impact of the reduction levers)

Emission tree 2011

Clinker

Combustion 0,221 tCO₂ e/t clinker
 0,766 tCO₂ e/t clinker

Humid process

Combustion 0,655 tCO₂ e/t clinker
 1,2 tCO₂ e/t clinker

White clinker

Combustion 0,442 tCO₂ e/t clinker
 0,987 tCO₂ e /t clinker

Cement

Combustion 0,545 tCO₂ e/t clinker
 0,545 tCO₂ e/t clinker

Process

Process 0,545 tCO₂ e/t clinker
 0,221 tCO₂ e/t clinker

Emission factor

Emission factor

Substitutes

% materials

Min 5% vs 95% clinker

Composed

% materials

Max 95% vs 5% clinker

0,766 tCO₂ e/t clinker

0,814 tCO₂ e/t clinker

1,2 tCO₂ e/t clinker

0,987 tCO₂ e /t clinker

0,545 tCO₂ e/t clinker

0,545 tCO₂ e/t clinker

0,59 tCO₂ e/t cement

3635 Mt cement

2163 M tCO₂ e

0,59 tCO₂ e/t cement

3200 Mt grey clinker

3200 Mt grey clinker

0,814 tCO₂ e/t clinker

1,2 tCO₂ e/t clinker

0,987 tCO₂ e /t clinker

White clinker

3200 Mt grey clinker

0,814 tCO₂ e/t clinker

1,2 tCO₂ e/t clinker

0,987 tCO₂ e /t clinker

White clinker

% materials

Min 5% vs 95% clinker

% materials

Max 95% vs 5% clinker

Substitutes

57% tons

43% tons

Portland

Composed

NOTE: Excludes electricity which is included in the energy sector
SOURCE: (0) IEA 2011 (1) CBR & Holcim 2011 interviews
(2) 2010 Belgian GHG inventory (3) USGS, (4) Climact analysis (5) Febelcem

Sector provided with an opportunity to review these figures

Figures of July 2014
Assumptions for consumption and emissions are specified

Model assumptions (2011) \(^{(1, 2)}\)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production (Mt)</td>
<td>3635</td>
</tr>
<tr>
<td>Specific Consumption (PJ/MT= GJ/t Cement)</td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>0,35</td>
</tr>
<tr>
<td>Solid HC</td>
<td>1,88</td>
</tr>
<tr>
<td>Liquid HC</td>
<td>0,31</td>
</tr>
<tr>
<td>Gaseous HC</td>
<td>0,23</td>
</tr>
<tr>
<td>Biomass &amp; Waste</td>
<td>0,14</td>
</tr>
<tr>
<td>Heat</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2,92</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specific emissions (tCO2/t cement)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion CO(_2) e</td>
<td>0,21</td>
</tr>
<tr>
<td>Process CO(_2)</td>
<td>0,38</td>
</tr>
<tr>
<td>Process CH(_4)</td>
<td>0,03</td>
</tr>
<tr>
<td>Process N(_2)O</td>
<td>0,03</td>
</tr>
<tr>
<td><strong>Total CO(_2)</strong></td>
<td><strong>0,59</strong></td>
</tr>
<tr>
<td><strong>Total CH(_4)</strong></td>
<td><strong>0,03</strong></td>
</tr>
<tr>
<td><strong>Total N(_2)O</strong></td>
<td><strong>0,03</strong></td>
</tr>
<tr>
<td><strong>Total CO(_2) e</strong></td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** scope covers steel & alloys making (but not the use phase nor the materials extraction phase

SOURCE: (1) IEA (2) MIDREX.com website
Global Calculator

Emission tree (modelled)

Model Emission tree 2011

Cement GHG emissions
3635 Mt cement (0)
2163 Mt CO₂e (0)
0,59 tCO₂e/t cement (0)

Combustion
0,212 tCO₂e/t cement (3)

Solid fuels

Liquid fuels

Gaseous fuels

Biomass

Process
0,382 tCO₂e/t cement (3)

Heat

Electricity

Calculations:

<table>
<thead>
<tr>
<th></th>
<th>Quantity</th>
<th>Emission factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid fuels</td>
<td>1,885 TWh/Mt cement</td>
<td>0,312 Mt CO₂e/TWh</td>
</tr>
<tr>
<td>Liquid fuels</td>
<td>0,313 TWh/Mt cement</td>
<td>0,255 Mt CO₂e/TWh</td>
</tr>
<tr>
<td>Gaseous fuels</td>
<td>0,228 TWh/Mt cement</td>
<td>0,185 Mt CO₂e/TWh</td>
</tr>
<tr>
<td>Biomass</td>
<td>0,135 TWh/Mt cement</td>
<td>0,0 Mt CO₂e/TWh</td>
</tr>
<tr>
<td>Heat</td>
<td>0,00 TWh/Mt cement</td>
<td>0,0 Mt CO₂e/TWh</td>
</tr>
<tr>
<td>Electricity</td>
<td>0,355 TWh/Mt cement</td>
<td>Defined by the model</td>
</tr>
</tbody>
</table>

Cement specific emission factor for biomass & waste could be added in future version of the model

SOURCE: (0) IEA 2011, (2) 2010 Belgium GHG inventory (3) 2010 Walloon region energy balance, (4) Climact analysis
**List of actions & levers assessed**

**Design**
- Changing product and material specifications to answer the same needs with less materials
  
**Smart design**

**Switch**
- Change materials to enable a low carbon product (over the product lifetime)
  
**In buildings/Infr. : To green plastics & to timber**

**Recycling**
- Recycle the product or the material
  
**Product recycling**

**Material recycling**

**Steel/composed cement**

**SOURCE:** Climact
**Smart design**

Better specified cement can fulfil the same requirements with lower volumes

---

**Rationale for a smarter design**

- Use of optimized moulds could enable to use up to 40% less concrete in some places (1)
- Concrete strength is proportional to the amount of cement in the mix, so lower strength concrete can use less cement
- Current rationalisation of mixes on a site leads to above required use of cement
- Use of stainless steel, or plastic coated bars removes the need for concrete to protect the steel (to use with caution as stainless steel is more emissions intensive)

---

**Cement demand reduction enabled by smart design (%)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Ambition 1</th>
<th>Ambition 2</th>
<th>Ambition 3</th>
<th>Ambition 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2020</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>2030</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>2040</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>2050</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
<td>20%</td>
</tr>
</tbody>
</table>

---

**Product life time is not addressed in this section, it is however expected to have a major impact, with a high proportion of Chinese buildings currently lasting 20-30 years while they could be stretched to 150...**

---

**SOURCE:** With both eyes open

(1) With both eyes open (Orr et Al. (2010), research of efficient concrete shapes)
Material switch
Cement is one of the cheapest option to build durable constructions

Embodied energy (Gj/t)

Relative useful costs (1)
(% relative to steel at 100%)

- Concrete has a relatively low embodied energy and cost required to convert it in useful form
- Cement substitutes all have advantages and drawbacks

NOTE: (1) Refer to “With both eyes open” for more details on the definition of useful costs
SOURCE: (1) With both eyes open
# Material switch

Cement can be substituted by less CO₂ intensive materials

## Materials which can replace /be replaced by concrete

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Cement replacement assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>Buildings</td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
<td></td>
</tr>
</tbody>
</table>

### Aluminium
- Strength
- Recyclability
- Higher cost & embodied energy
- Not modelled
- Not modelled

### Steel
- Strength
- Recyclability
- Compatibility (rebar)
- Higher cost & embodied energy
- Requires protection against corrosion
- Not modelled
- Not modelled

### Plastics
- Strength
- No recyclability
- Higher embodied energy
- Up to 5% concrete can be replaced by insulation materials (HVC)
- Up to 5% concrete can be replaced by insulation materials (HVC)

### Stone & Masonry
- Strength
- lower embodied emissions
- Must be reinforced with mortar (from cement)
- Cannot be reinforced or moulded into shapes
- Not modelled
- Not modelled

### Timber
- high strength and stiffness per density (1)
- Less durable, requires protection against fire and rot, less stable
- Up to 20% concrete can be replaced by timber
- Not modelled

**NOTE :** (2) Historically, two product mixes are used in constructions. The “Continental approach” uses more concrete, while the “British approach” uses more steel.

**SOURCE:** (1) With both eyes open (Orr et Al. (2010), research of efficient concrete shapes)
Material switch
Proposed lever ambitions

Proportion of cement replaced by timber (%)

Proportion of cement replaced by chemical insulation materials (%)

- Timber being less stable & less homogeneous, a higher security factor must be taken into account when timber is used for the structure of buildings
- Biomass impacts is represented by the model

NOTE:
(1) Amount of one material required to replace another material is approximated through the specific Young modulus
(2) Assumption this material switch does not impact the product life
Material recycling: Aggregate
Cement is not recycled, but reused as an aggregate

Rationale on recycling potential

- Reversing the reaction that makes cement requires theoretically at least 1GJ/t, so cement is currently not “recycled” at present
- Creating block components reusable at the end of life is an option (with 2 technical options)
  - Chemical connectors
  - Mechanical connections, to provide a “Lego” interface
- Concrete can be crushed to make an aggregate which can be used to make concrete if mixed with new cement. However extra cement is required to bind the wider range of particle sizes in crushed concrete. This is then typically used for roads and infrastructures. This is not really recycling and is therefore addressed in the composed cement lever

NOTE: (1) Being researched in Japan, cfr Noguchi et al. (2011)
(2) This is typically expected with composite steel and cement blocks with a steel to steel interface
SOURCE: With Both Eyes Open

Proportion of cement recycled (%)

<table>
<thead>
<tr>
<th>Year</th>
<th>Ambition 1</th>
<th>Ambition 2</th>
<th>Ambition 3</th>
<th>Ambition 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2020</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2030</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2040</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2050</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Figures of July 2014
Global Calculator

Process improvements: Composed cement
Composed cement market share has increased historically…

World and regional cement substitutes evolution
(% of the cement production)

- Mineral components can be added to the clinker to obtain de cement (flying ashes, blast furnace slag, others), if those are superior to 5%, we get composed cement. Steel cement is a type of composed cement.
- Substitute share has increased globally and across all regions. China & India recently increased very firmly.

NOTE: Composed cement includes steel cement
SOURCE: WBCSD Cement Sustainability initiative
## Process improvements: Composed cement

There is a resource limit to the amount of clinker that can be substituted

### Types of clinker substitution

<table>
<thead>
<tr>
<th>Types of clinker substitution</th>
<th>Impact on the cement characteristics</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Granulated Blast Furnace Slag (GGBS)</td>
<td>Adds long term strength and durability (but lower initial strength and slower curing)</td>
<td>250 Mt/year</td>
</tr>
<tr>
<td>Pulverised Fly Ash (PFA)</td>
<td>Improves concrete workability and long term strength (but lower initial strength)</td>
<td>900 Mt/year</td>
</tr>
<tr>
<td>Pozzolan</td>
<td>Improves durability and workability (but lower initial strength)</td>
<td>300 Mt/year</td>
</tr>
<tr>
<td>Limestone</td>
<td>Improves workability but reduces strength and durability</td>
<td>Widely available</td>
</tr>
<tr>
<td>Crushed concrete</td>
<td>Does require slightly more cement</td>
<td>3500 Mt/year</td>
</tr>
</tbody>
</table>

**Annual supplies of GGBS, PFA & Pozzolan currently total 1450 Mt**

And Limestone substitution has also downsides and is only used in level 4

Including crushed cements enables close to 5000 Mt

---

**NOTE:** Mineral components can be added to the clinker to obtain de cement (flying ashes, blast furnace slag, others), if those are superior to 5%, we get composed cement. Steel cement is a type of composed cement.

**SOURCE:** With Both Eyes Open, IEA Cement roadmap, Carbon war room (WBCSD 2009, Holcim 2009)
Process improvements: Composed cement
IEA scenarios forecast a substitution rate between 28-34%

Cement substitution (%)

- Prefabricated sector requires Portland cement (95% clinker) to dry faster
- Other applications can be satisfied with CEM III C cement (10% clinker and 90% steel slag). This cement can reach higher solidity levels than Portland cement but takes longer to dry.
- The access to substitution mineral components is getting harder.
- Upper boundary, in case of high growth demand, with current substitute production is of 1450/5521 Mtons, neglecting lime, corresponds to 26% others.
- If the cement industry were to use significantly more steel slag, its price would be expected to increase.

NOTES: Major hypothesis: no emissions are allocated to the steel slag, considering it as a waste from the steel sector
Substitution potential is not applicable to white cement
Intermediary figures are a Climact assumption for 2,4 & 6 DS
SOURCE: (1) IEA ETP 2012 and IEA 2009 Cement Roadmap (2) Fortea CBR and Holcim consultations, Febelcem annual report
Process improvements: Composed cement
Proposed lever ambitions

Proportion of substitutes in the cement composition (%)

Rationale for the different ambitions

4
- Ambition for a 100% transition to CEM III C, which is possible but will imply higher storage costs
- Implies a substitution rate of 90%
- We could consider it applied to all except prefabricated industry (if quantified by the sector)

3
- Ambition aligned with IEA 2DS roadmap

2
- Intermediary ambition

1
- Ambition aligned to the IEA 6DS roadmap

SOURCE: Cement consultation, Climact analysis
Carbon intensity of material production
Process improvements, fuel mixes, energy efficiency & CCS are then assessed

List of actions & levers assessed

- **Process improvement**
  - Towards fuels which emit less CO₂

- **Fuel substitution**
  - Modification of processes

- **Energy efficiency**
  - Reduce mechanical and thermal losses
  - Recuperate thermal energy (CHP)

- **End of pipe technologies**
  - Carbon capture and storage

**NOTE:** Process choice has consequences on applicability of other levers. Some combinations are exclusive whilst others can be added in sequential order.

**SOURCE:** (1) (redundant with Ulcored while we represent Hisarna in this analysis)
3 Process improvements
The share of BAT clinker production is increasing (along the dry technology, with preheater and precalciner)

Clinker production per technology
(M tons clinker)

• The choice of using a dry or humid choice is linked to the exploited quarry type
• We assume this improvement is included in the IEA specific consumption projections (in energy efficiency improvements)
• « green concrete », a new low carbon process (using magnesium oxyde instead of calcium), enables to obtain cement through a less CO₂ intensive process. It is currently not modelled

NOTE: (1) Green concrete not considered mature technologically; the entity commercializing it does not exist any more. Furthermore, there is a lack of available data on the technology
SOURCE: GNR participants to the CSI
### Alternative fuels

The alternative fuels proportion has strongly increased and reaches one the highest European levels.

#### Alternative fuel consumption in the cement sector (%)

<table>
<thead>
<tr>
<th>Year</th>
<th>Alternative fuels</th>
<th>Other fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 (4)</td>
<td>4%</td>
<td>96%</td>
</tr>
<tr>
<td>2050 ETP 2DS</td>
<td>30%</td>
<td>70%</td>
</tr>
<tr>
<td>2050 roadmap (3)</td>
<td>37%</td>
<td>63%</td>
</tr>
<tr>
<td>2050 roadmap (4)</td>
<td>30%</td>
<td>70%</td>
</tr>
</tbody>
</table>

#### Current situation
- Assumption mostly biomass and not waste

#### Potential evolution
- 30% biomass in 2DS
- 0% risk (waste and biomass could become inaccessible)
- 100% potential (contrarily to some industries, cement does not absorb the biomass and waste impurities)

#### Barriers:
- There are access problems to alternative fuels (biomass and waste)
- There are currently no financial incentives for waste incineration

---

**NOTE:** We assume biomass & waste combustion emissions at 0 in the first version of the calculator

**SOURCE:** (3) IEA Cement Technology RoadMap (4) IEA ETP 2012
## Alternative fuels
### Portion of alternative fuels in 2050

**Proportion of alternative fuels (%)**

<table>
<thead>
<tr>
<th>Ambition</th>
<th>Rationale for the different ambitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Biomass is too expensive or inaccessible</td>
</tr>
<tr>
<td>2</td>
<td>Constant use of substitutes (4 %=6% of coal)</td>
</tr>
<tr>
<td>3</td>
<td>Strong increase (30% = 46% of coal)</td>
</tr>
<tr>
<td>4</td>
<td>Entire mix (65% = 100% of coal)</td>
</tr>
</tbody>
</table>

**Figure of July 2014**

SOURCE: Cement consultation, Climact analysis
Energy efficiency
Clinker energy efficiency can increase by more than 15%

Specific consumption evolution forecast
(GJ/t clinker)

- IEA 2009 specific consumption objective is 18% lower than the world 2012 average
- The minimum theoretical energy requirement is 1.8 GJ/tonne\(^{(1)}\)

NOTES:
Energy efficiency improvements are expected to be lower in white cement
The later only represents 2% of the production

SOURCE: IEA 2009 technology roadmap
(1) With both eyes open (p.64 'Cement chemistry', Taylor, H., 1990)
Several factors support the specific consumption reduction:

- The rising proportion of dry process with pre-heaters and pre-calciners
- The energy price increase

If all plants used BAT, the average world specific consumption could be reduced by 1.1 GJ/ton cement

**Current Specific consumption**

(GJ/t clinker)

<table>
<thead>
<tr>
<th>2012 average</th>
<th>2011 -30% for BAT &amp; EE</th>
<th>Vertical shafts</th>
<th>Long drying process</th>
<th>Long drying process with pre-...</th>
<th>IEA roadmap 2030</th>
<th>IEA roadmap 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.9</td>
<td>2.73</td>
<td>4.8</td>
<td>6.7</td>
<td>3.5</td>
<td>3.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

**Energy efficiency gains encompass process improvements**

**High**

**Low**

SOURCE: IEA ETP 2012
Energy efficiency
There are significant regional differences

Specific consumption evolution
(MJ/t clinker)\(^{(1)}\)

- Two thirds of the people making cement are in China, while China only produces 40% of the world's cement, this is because they are in small factories using older technologies\(^{(2)}\)
- India is also known for currently having old factories\(^{(2)}\)
- Old factories often use the wet process\(^{(2)}\)
- There is more improvement potential in developed countries (as developing countries have recently invested in new technologies)\(^{(3)}\)

Feedback appears contradictory; recommendations?
Energy efficiency (CHP)
Proposed lever ambitions

Percentage of electricity production through CHPs (%)
Energy efficiency
Proposed lever ambitions

Specific consumption improvements
(Gj/ton clinker, % reduction vs 2010)

- Ambition 1: -5%
- Ambition 2: -9%
- Ambition 3: -18%
- Ambition 4: -30%

Lever cost (€/t crude steel)

<table>
<thead>
<tr>
<th>Input (fuel &amp; material)</th>
<th>-X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other opex</td>
<td>0</td>
</tr>
<tr>
<td>Capex (Assuming 5 years payback on energy savings)</td>
<td>229 +X</td>
</tr>
</tbody>
</table>

SOURCE: Cement consultation, Climact analysis
Typical ranges of costs of emission reductions from industrial applications of CCS
(USD/tCO$_2$e avoided)

- ~50%-70% of all new large plants and 30%-45% of retrofitted plants equipped with CCS by 2050 in the 2DS
- Deploy 120 to 140 kilns with CCS by 2030, 300 to 400 by 2040 and 500 to 700 by 2050
- Capture costs of USD 100 € (2030) and USD 75 € (2050) for PC and USD 50 € (2030) and USD 40 € (2050) for oxyfuels.

NOTE: The range of costs shown here reflect the regional average costs of applying CCS in each sector, and, therefore, the overall cost of abatement in a sector will be affected by the assumed level of CCS uptake in each sector (IEA, 2009 and IEA and UNIDO 2011). These costs include the cost of capture, transport and storage, but do not assume that storage generates revenues (i.e. CO$_2$ storage through enhanced oil recovery (EOR) is not considered as a storage option.

SOURCE: ETP 2012, IEA
Carbon Capture & Storage
Proposed lever ambitions

Emissions capture rate by CCS (%)

Rationale for the different ambitions

<table>
<thead>
<tr>
<th>Ambition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ambition 1: 0%</strong></td>
<td>- No implementation</td>
</tr>
<tr>
<td><strong>Ambition 2: 30%</strong></td>
<td>- Only largest sites</td>
</tr>
<tr>
<td><strong>Ambition 3: 51%</strong></td>
<td>- Ambition 3 aligned to ETP 2012 ambition of 40-45% plants</td>
</tr>
<tr>
<td><strong>Ambition 4: 85%</strong></td>
<td>- All sites, 85% capture rate</td>
</tr>
</tbody>
</table>

Lever cost (2)

<table>
<thead>
<tr>
<th>Input (fuel &amp; material)</th>
<th>0.33 TWh Elec/Mt captured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other opex</td>
<td>$20 USD/ton captured</td>
</tr>
<tr>
<td>Capex</td>
<td>$60 USD/ton captured</td>
</tr>
</tbody>
</table>

SOURCE: Cement consultation, Climact analysis
Reduction potential
Final Materials demand according to different trajectories (after design, switch & recycle)

Cement Production Trajectories for different ambition levels (simulating a constant clinker rate)\(^{(1,2)}\)
(Mton cement)

<table>
<thead>
<tr>
<th>Year</th>
<th>Delta 10-50,%</th>
<th>Implied demand per person</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>-50%</td>
<td>912 kg/person/year</td>
</tr>
<tr>
<td>2015</td>
<td>+140%</td>
<td>565 kg/person/year</td>
</tr>
<tr>
<td>2020</td>
<td>+49%</td>
<td>328 kg/person/year</td>
</tr>
<tr>
<td>2025</td>
<td>-14%</td>
<td>194 kg/person/year</td>
</tr>
<tr>
<td>2030</td>
<td>-49%</td>
<td></td>
</tr>
<tr>
<td>2035</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2040</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2045</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2050</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE:  
(1) The population follows the average UN projection in all four trajectories  
(2) Other sectors are impacted by these transitions (e.g. additional productions are created in the timber sector)

SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Details for ambition level 3

Cement production for ambition level 3
(M tons, % of 2011)

Trajectories(1) in 2050

NOTE:  
(1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions
SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Emissions according to different trajectories

Cement GHG emission trajectories for different ambition levels\(^{(1,2,3)}\)
(Mton CO\(_2\)e)

<table>
<thead>
<tr>
<th>Delta 10-50%</th>
<th>Specific emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>+135%</td>
<td>596 kg /ton cement</td>
</tr>
<tr>
<td>-18%</td>
<td>334 kg /ton cement</td>
</tr>
<tr>
<td>-74%</td>
<td>201 kg /ton cement</td>
</tr>
<tr>
<td>-95%</td>
<td>70 kg /ton cement</td>
</tr>
</tbody>
</table>

NOTES:
(1) The population follows the average UN projection in all four trajectories
(2) Excluding biomass related reductions & electricity related emissions
(3) Other sectors are impacted by these transitions (e.g. additional emissions are created in the timber sector)

SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Details for ambition level 3 (1)

Cement GHG emissions in 2050, for ambition level 3(1,2), using different levers(3)
(MtCO₂e, % of 2010)

NOTES:
(1) The population follows the average UN projection in all four trajectories
(2) Excluding biomass related reductions & electricity related emissions
(3) Other sectors are impacted by these transitions (e.g. additional emissions are created in the aluminium and plastics sectors)
Percentage reductions are calculated vs the 2010 baseline
SOURCE: IEA ETP 2012, Global calculator model
Costs
In cement, most of the potential comes from the use of composed cement.

GHG abatement curve for the year 2050 (trajectory 2, ambition 4)
€/tCO$_2$e, % emission abatement in 2050 (% of 2008 level)

- Energy efficiency
- Product mix
- CCS

To obtain the 99% evolution of ambition 4, add the 2010-2050 21% reduction

NOTE: Including biomass potential
SOURCE: IEA ETP 2012, Global calculator model
2050 evolution of materials and emissions

Materials demand evolution
  • Cross sector demand
  • Cross sector material switch
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper & Timber

Reduction potential on the manufacturing processes
  • Resulting emissions
  • Discussion on ambition levels across sectors
  • Discussion on CCS
  • Steel
  • Chemicals
  • Aluminium
  • Cement
  • Paper, Timber & Other
Reduction potential
Details for ambition level 3

Paper production for ambition level 3
(M tons, % of 2011)

Trajectories\(^{(1)}\) in 2050

NOTE: (1) The population follows the average UN projection in all four trajectories
(2) Assuming biomass emits, not including electricity related emissions

SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Details for ambition level 3 (1)

Paper GHG emissions in 2050, for ambition level 3(1,2), using different levers(3)
(MtCO$_2$e, % of 2010)

NOTES:  (1) The population follows the average UN projection in all four trajectories
(2) Excluding biomass related reductions & electricity related emissions
(3) Other sectors are impacted by these transitions (e.g. additional emissions are created in the aluminium and plastics sectors)
Percentage reductions are calculated vs the 2010 baseline
SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Details for ambition level 3

Timber production for ambition level 3
(M tons, % of 2011)

Trajectories\(^{(1)}\) in 2050

NOTE:  
(1) The population follows the average UN projection in all four trajectories 
(2) Assuming biomass emits, not including electricity related emissions 
SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Details for ambition level 3 (1)

Timber GHG emissions in 2050, for ambition level 3(1,2), using different levers(3)
(MtCO₂e, % of 2010)

NOTES:
(1) The population follows the average UN projection in all four trajectories
(2) Excluding biomass related reductions & electricity related emissions
(3) Other sectors are impacted by these transitions (e.g. additional emissions are created in the aluminium and plastics sectors)
Percentage reductions are calculated vs the 2010 baseline
SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Details for ambition level 3

Other production for ambition level 3
(M tons, % of 2011)

Trajectories\(^{(1)}\) in 2050

NOTE:  
(1) The population follows the average UN projection in all four trajectories  
(2) Assuming biomass emits, not including electricity related emissions

SOURCE: IEA ETP 2012, Global calculator model
Reduction potential
Details for ambition level 3 \(^{(1)}\)

Other GHG emissions in 2050, for ambition level 3\(^{(1,2)}\), using different levers\(^{(3)}\)
(MtCO\(_2\)e, % of 2010)

**NOTES:**
1. The population follows the average UN projection in all four trajectories
2. Excluding biomass related reductions & electricity related emissions
3. Other sectors are impacted by these transitions (e.g. additional emissions are created in the aluminium and plastics sectors)

Percentage reductions are calculated vs the 2010 baseline

**SOURCE:** IEA ETP 2012, Global calculator model

Figures of July 2014
Thank you.

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