Decarbonisation Technology

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Powering the Transition to Sustainable Fuels & Energy

Sustainable solutions with industrial clusters: Part 1

Decarbonising an industrial cluster requires a methodical techno-economic evaluation based on the carbon abatement cost curve

Joris Mertens
KBC (A Yokogawa Company)

Industrial clusters represent a substantial part of global greenhouse gas emissions. The combined annual CO_2 emissions of the 20 signatory clusters of the World Economic Forum exceed 600 million tonnes (WEF, 2023). Meanwhile, the European Expert Group on Clusters identifies at least 3,000 industrial clusters in the EU alone (European Commission, 2021).

Rather than defined in terms of size and industry type, industrial clusters refer to various facilities in reasonable proximity but generally owned by different entities. Clusters are better positioned to successfully decarbonise than isolated individual industrial sites because of the higher potential to integrate resources via collaboration.

Accomplishing this potential, however, is complex. It involves digitalisation, process technology, economics and, possibly most challenging, trust and active collaboration between players across different industries as well as potential competitors.

Optimising industrial systems include three dimensions: Scope, Scale and Frequency, as shown in **Figure 1**. Scope refers to the utilities, feeds, and products integrated in the system optimisation. Scale pertains to the selection of sites within the industrial cluster. Lastly, Frequency relates to the time dimension of cluster optimisation (real-time, daily, monthly). The industrial system is optimised when the cluster operates as a system of systems (SoS) that accounts for all aspects of Scope, Scale, and Frequency.

Due to the complexity, such an integrated SoS for a large industrial zone does not yet exist, posing the question: What is the best approach to building one?

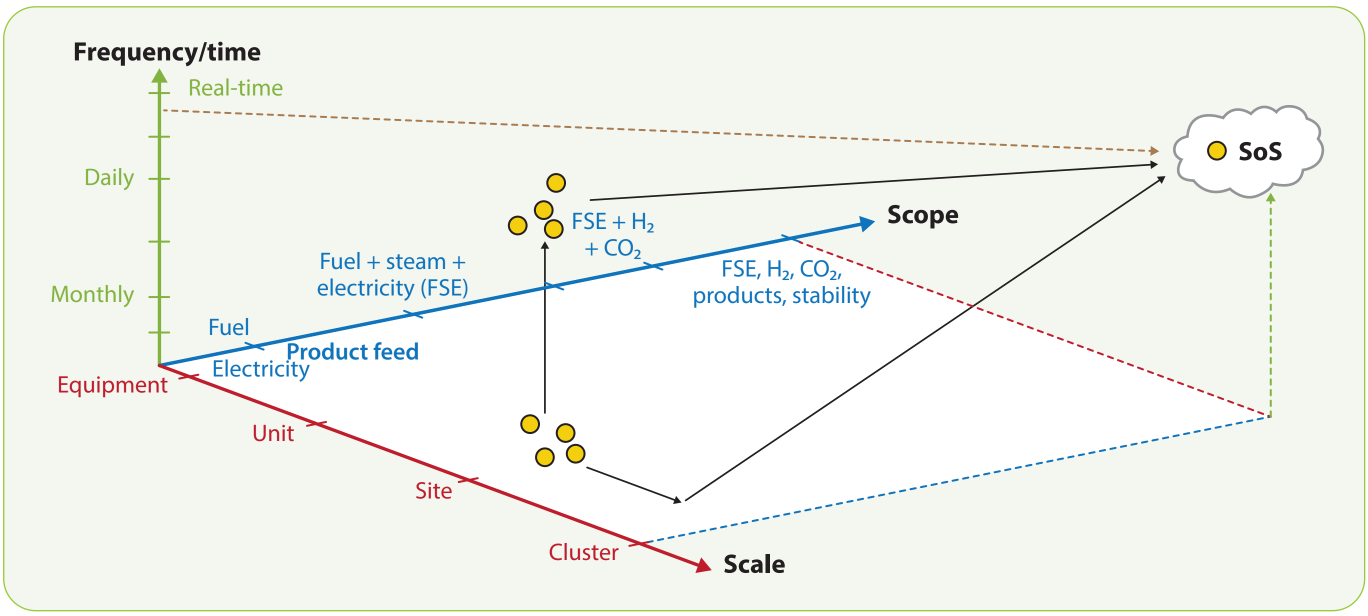

Figure 1 System of systems (SoS) optimisation

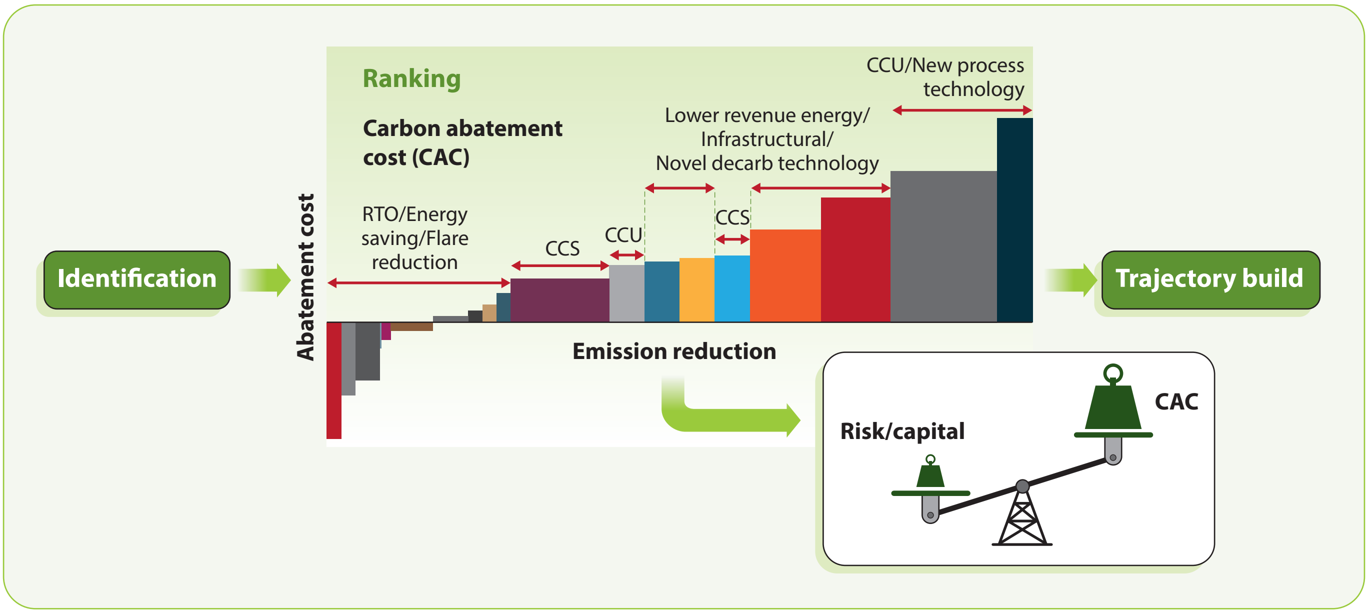

Figure 2 Decarbonisation trajectory development

A recommended approach involves two work streams: an offline desktop trajectory development, which uses a model or digital twin of the system, and an implementation stream.

Part 1 of this article discusses developing a decarbonisation trajectory, while Parts 2 and 3 will focus on implementing the decarbonisation trajectory and how to sustain the benefits of an optimised industrial cluster.

It is important to note that the two work streams should not be fully separated exercises.

Decarbonisation trajectory development

The trajectory development for decarbonisation is a work stream conducted offline. As shown in **Figure 2**, it consists of the following consecutive steps:

- Identify the steps that can contribute to decarbonisation.
- Compile a ranking order for implementation based on carbon abatement cost while accounting for risk and capital requirements.
- Build a trajectory.

This exercise applies to decarbonising both individual sites and industrial clusters. The size of industrial clusters and the fact that clusters are systems with distributed ownership further complicates the process.

Identifying decarbonisation contributors

The plans and decarbonisation targets for the individual sites are the basic inputs for developing the decarbonisation strategy for the cluster. Additionally, the future infrastructure and system characteristics and constraints need to be understood. This includes the following factors:

- Carbon intensity of grid electricity
- New industrial entrants and leavers
- CO_2 storage options
- Electricity grid constraints
- Infrastructural projects considered or planned relating to, for example, the power grid, district heating, H_2 or CO_2 infrastructure.

The technical options can be bundled into the following classes:

- **Low-to-medium investment cost options** include real-time optimisation, flaring reduction, and energy system optimisation that require limited equipment changes, such as exchangers and smaller drivers. Additionally, it involves a small investment in piping infrastructure and limited enhancements to site or cluster power infrastructure.
- **Inter-site collaboration** will be incentivised when adjacent sites integrate utility systems. Although capital costs can vary widely, they are expected to range from medium to very high. However, optimising production processes by exchanging products or optimising product logistics presents additional opportunities to offset costs.
- **High to very high investment** options involve optimising capital energy systems (such as large compressors, gas turbines), revamping process units, fortifying the major grid, and

creating district heating systems. With a capital cost reaching billions for a large steel plant, switching coke-fed blast furnace steel making to direct reduced iron (DRI) using hydrogen can be the ultimate example of a site/process-related decarbonisation project.

- **Novel technology or application** of existing technologies such as advanced electrification (e-furnaces/boilers), hydrogen or ammonia firing heat pumps.
- **Carbon capture and storage** (CCS) is a form of waste disposal. In spite of the high energy consumption and capital cost involved, CCS is a lower-cost emission reduction option for some applications than what is offered by current alternatives.
- **Carbon capture and utilisation** (CCU) can contribute significantly to a decarbonisation strategy. However, it runs into some significant cost constraints:
  - A techno-economic study evaluated nine different carbon utilisation technologies (Mertens, et al., 2022) (Mertens, et al., 2023). The findings highlighted that most of these technologies require large amounts of expensive green hydrogen, which renders them economically unviable unless the products generated are valued substantially higher than their fossil counterparts.

One high-value market already exists for sustainable aviation fuel (SAF). From 2030 onwards, specific e-SAF mandates will provide more support for carbon utilisation.

  - Burning fuels produced from CO_2 originating from fossil sources still results in net CO_2 emissions. Therefore, producers of fossil CO_2 should not be exempt from emission taxation or trading scheme obligations, even when the CO_2 generated is used to make products.

European legislation will likely mandate that CO_2 used as a raw material to produce new products stems from either biogenic sources or direct air capture rather than from combusted fossil fuels. This approach increases operating costs for carbon utilisation projects and may limit the available CO_2.

Bundling provides a preliminary ranking order of all the emission reduction options.

Ranking: Carbon abatement cost, risk, and capital

Carbon abatement cost

The trajectory development is driven by the carbon abatement cost (CAC) curve that more rigorously ranks the different carbon reduction initiatives according to the costs involved in reducing CO_2 emissions, as shown in **Figure 3**. The CAC for decarbonisation initiatives is calculated from cash flow elements, capital expenditures, and capital cost details such as debt and equity costs, IRR/NPV requirements, and loan duration.

Abatement cost can be estimated as follows:

- Using a financial model that credits CO_2 emissions savings, with the abatement cost

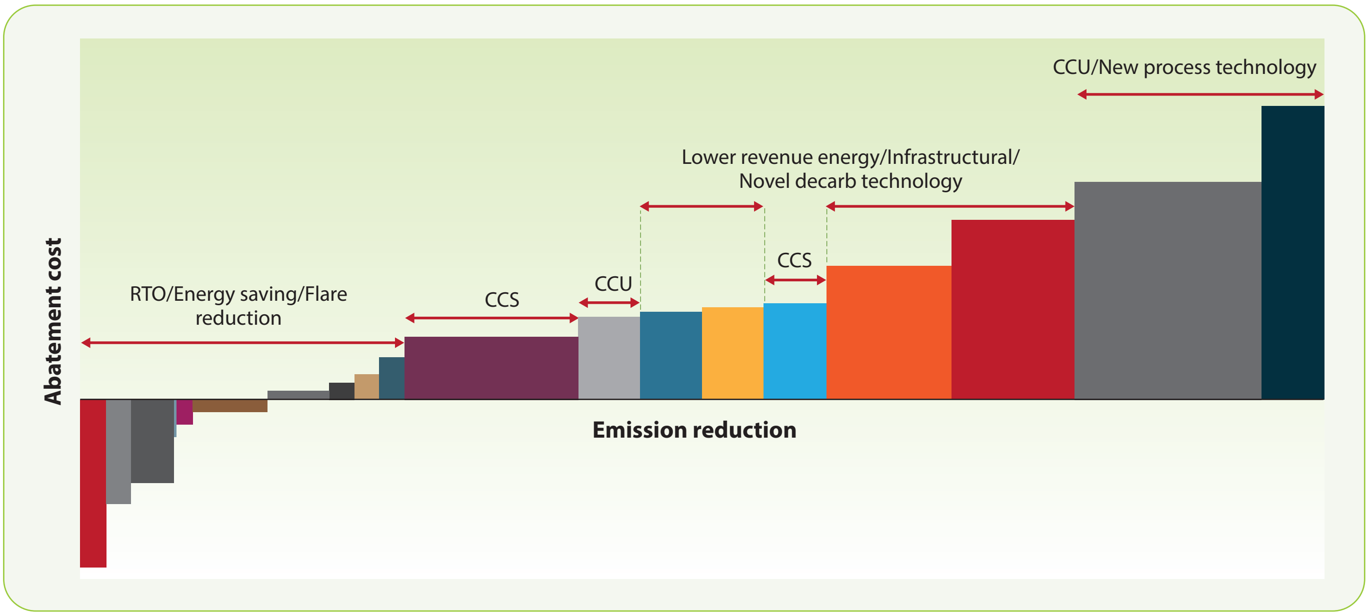

Figure 3 Carbon abatement cost curve

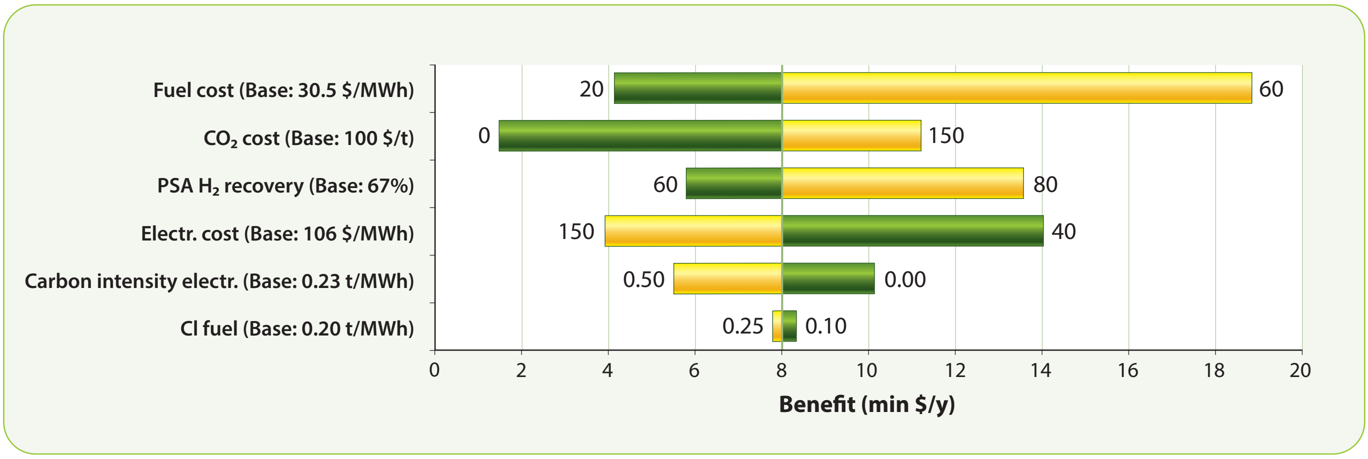

Figure 4 Sensitivity analysis

determined by the level of that credit at which a specified financial performance is achieved, such as a positive net present value (NPV) at a set internal rate of return (IRR).

- Applying a simpler approach annualises capital costs:

$$\text{Annualised capital cost} = \text{Capital spent}^* \frac{i * (1+i)^n}{(1+i)^n - 1}$$

where
i = cost of capital
n = duration / project life

The CAC will be the CO_2 credit at which the cash flow equals the annualised capital cost.

This simplified approach will slightly underestimate the carbon cost compared to the detailed method that accounts for construction time, possible low initial utilisation rate after project completion, turnarounds, taxation, and other factors. However, the simplified approach fits a high-level screening study with multiple decarbonisation projects where the goal is to establish ranking rather than estimate an accurate abatement cost.

The CAC is a powerful tool that presents projects in an order that can be directly translated into a trajectory. However, risk and capital cost must be weighed as well.

Risk and capital cost

When ranking carbon abatement projects, the following technical, economic, commercial, and legal constraints or uncertainties represent a risk and, therefore, will need to be considered:

- **Technical**: The availability of green electricity and hydrogen, CO_2 storage capacity and transportation infrastructure, technological readiness level (TRL), and unanticipated cross-project or cross-site.
- **Economic**: Accurately estimating investment costs, feed and hydrogen costs, product value, inflation, taxation, and infrastructure projects such as power grids, H_2/CO_2 headers, and district heating.
- **Commercial and legislative**: Market demand, land availability, and obtaining permits.

These factors need to be compiled to assess the risks related to the different emission reduction initiatives. This can be done using methodologies such as sensitivity studies or Monte Carlo Analysis. **Figure 4** is a Tornado Diagram that shows how sensitive a project's cash flow is to certain independent input variables. Depending on the outcome, the priority of implementation may change, or further analysis may be required.

These methods are useful but require an assessment or assumption of risk distribution themselves. Therefore, first performing preparatory investigations into the risk factors, such as those listed in the Identifying decarbonisation contributors section, are as important as the risk assessment itself.

Capital requirements may render some projects hard to implement. As a result, the project may have to be either discarded or phased back. However, collaboration with neighbouring sites may substantially reduce the financial needs and risk. The best examples in the decarbonisation sphere probably involve implementing CCS hubs. This collaboration materialises due to distributing technical and financial burdens across all stakeholders.

Trajectory build

The development of a decarbonisation trajectory to carbon neutrality, for an individual site or a cluster, should be done in steps by building the following material and energy/emission balances and intermediate trajectories:

- **Base case**: The first step consists of establishing the current heat and utility balance.
- **Business As Usual Trajectory (BAUT)**: The next step in the evolution of material and utility balances, assuming the system itself does not change but only adapts to external factors. The BAUT is based on the expected future output for all industries in the site or cluster.

For instance, the refining sector faces a challenge as the demand for fossil fuels for road vehicles will drop, particularly in Europe. Polymer production may also be affected due to the need to reduce plastic waste. Unabated, the global annual production of plastics could increase from 400 to 1,600 million tonnes (Scott, et al., 2020). This massive volume is unsustainable if a substantial part of it is not recycled.

- **Stated policy trajectory (SPT)**: Outlines the system's evolution if existing plans and policies are implemented.

The industries within a cluster should have clear intentions and plans. An SPT is best developed based on plans with a certain technical and financial maturity. Furthermore, the stated policies of the different cluster entities must be aligned and consolidated: Are they based on the same assumptions, and can they be combined? Therefore, developing an SPT trajectory for a cluster of sites may require adjusting the individual SPTs to achieve overall coherence.

Additionally, a financial and risk evaluation may need to be performed.

- **Compliant trajectory (CT)**: Taking action to decrease emissions according to a set decarbonisation reduction trajectory.

Existing plans and strong commitments may fall short of ambitious net-zero targets. Therefore, the compliant trajectory includes actions in addition to the SPT to close the emissions trajectory gap.

“The industries within a cluster should have clear intentions and plans. An SPT is best developed based on plans with a certain technical and financial maturity”

Figure 5 directionally shows the options available to close the gap between the stated policy and compliant trajectories.

The impact of combined decarbonisation initiatives differs from the sum of individual steps. Therefore, properly assessing the decarbonisation initiatives requires a system-wide consolidation, as well as the right tools and stakeholder interactions. **Figure 6** shows how the trajectory is constructed:

❶ Pre-qualification and ranking, as previously described.
❷ BAUT build.
❸ SPT and CT build using the pre-qualified and

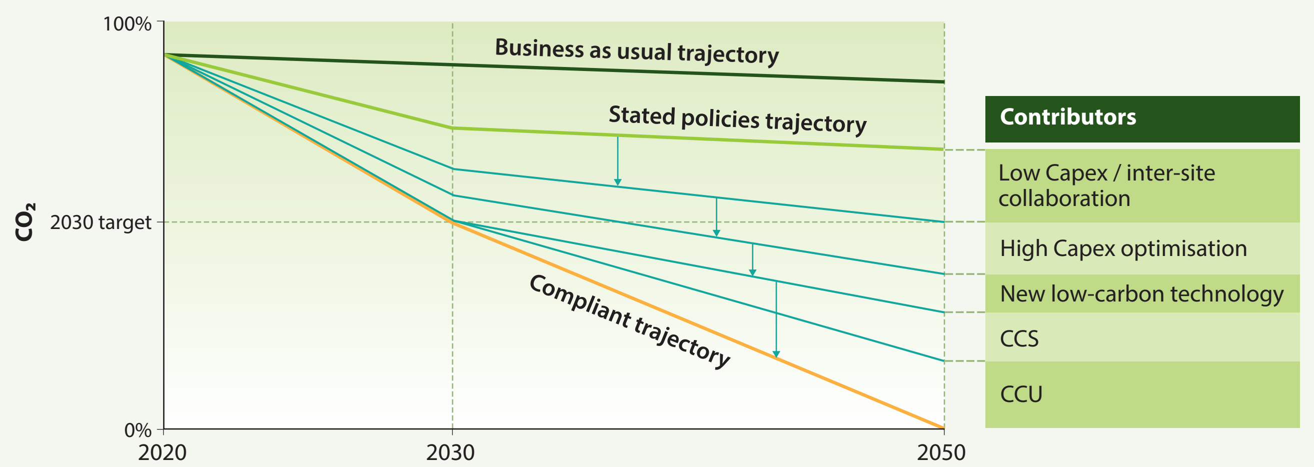

Figure 5 Decarbonisation trajectory development

ranked decarbonisation steps. The outcome results from three contributors:

i. **Accumulation**: Adding the different decarbonisation steps.

ii. **Interaction**: Accounting for interactions between the individual steps.

iii. **Time dimension**: A trajectory implies the steps will be implemented in a staggered order. A detailed impact assessment is required for at least two periods (2030 and 2050 in Figure 6), with possible interpolation for the intermediate periods.

Tools: energy system and process simulation

Spreadsheet modelling can be used to estimate the cumulative impact of different decarbonisation actions. However, it may not allow for establishing material and utility balances of the system accurately and even less for assessing the interaction between subsystems. An Integrated Process, Energy, Emissions and Economics Model (IP3EM) consisting of digital twins of the energy and process systems is the best possible tool to achieve this (Mitchell, 2023).

Stakeholder interaction

Even though technical evaluation is important, it is only accurate to the extent that the inputs and assumptions are realistic. Thus, close and regular interaction among industrial stakeholders is crucial, as discussed in the next section.

Trajectory development: cluster specifics

Challenges of cluster decarbonisation are similar to those of individual sites. However, the complexity and divided ownership pose additional challenges that need to be overcome to capture the potential synergies of cluster integration.

Complexity

In trajectory development, technical issues related to subsystems may arise, but risk management should also be considered and can be addressed as follows:

- **Partitioning the task**: Despite improvements in information software and hardware technology, the trajectory build methodology described in the previous section may be difficult to apply on large industrial clusters when time and resources are limited. Therefore, a sliced or phased approach can be used to develop a proof of concept case as a first step with a focus on:
  - A geographic subcluster only; for example, limit the Scale dimension of Figure 1.
  - Constrain the Scope dimension to what is expected to contribute most to decarbonisation, most likely energy.
- **Risk mitigation:** Preparedness is key to

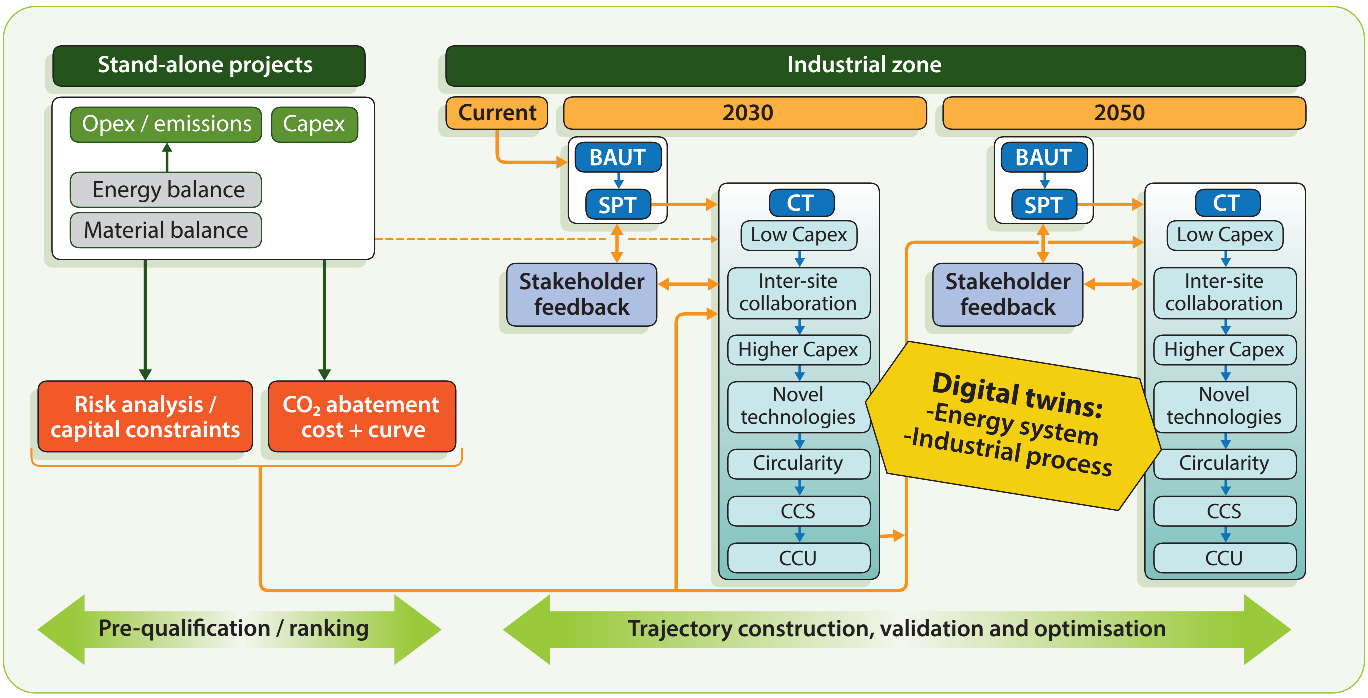

Figure 6 Decarbonisation trajectory build

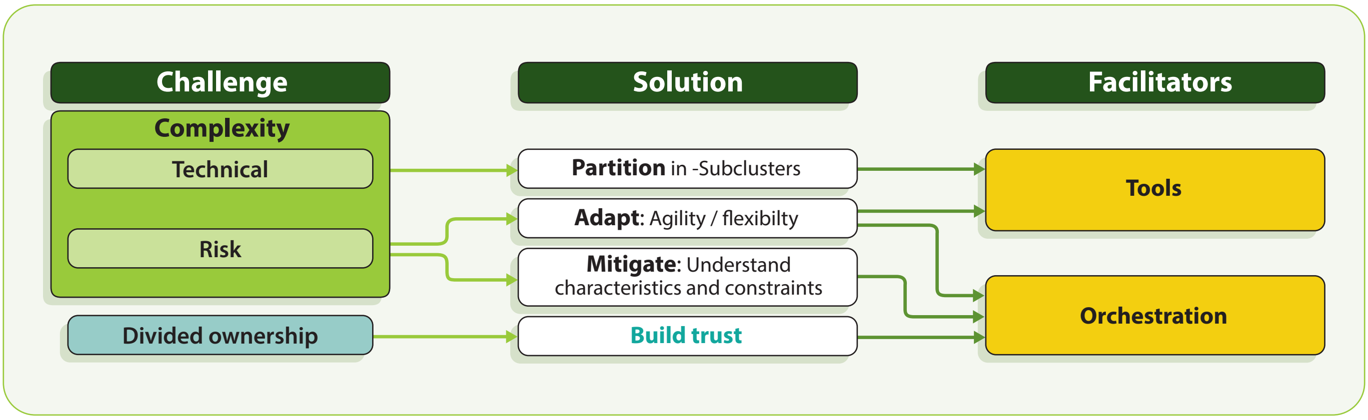

Figure 7 Cluster decarbonisation trajectory development challenges and facilitators

mitigating risk, as it means understanding the infrastructure and system characteristics and constraints, as explained in the Identifying Decarbonisation Contributors section.

- **Risk adaptation:** Flexibility and agility are achieved by:
  - Using adaptable tools that can swiftly adjust and reconstruct a trajectory when assumptions change.
  - Sustaining stakeholder interaction will help accelerate and get cluster-wide buy-in when changes occur.

Divided ownership and the orchestrator

The fact that clusters consist of entities owned by different parties, possibly competitors, should not significantly affect the trajectory. However, specifically for clusters, perceived risks, primarily around data sharing as well as capital and operational costs, will hamper trajectory development and likely impede implementation. Therefore, an independent orchestrator is required, even to start the journey, to bring the stakeholders together to create trust, as shown in **Figure 7**.

The orchestrator can be a business association, but these initiatives are primarily driven by government institutions with local business support.

The orchestrator also drives the trajectory development either by performing the task or appointing a third party when resources are unavailable. Part of the orchestrator's role involves setting the scene and identifying cross-industrial characteristics, constraints, and projects.

The orchestrator's role goes beyond co-ordinating collaboration between the process industries; it also provides critical input to utility providers and grid operators.

Conclusion

Developing a joint decarbonisation trajectory for a cluster of industrial sites will reduce both the operating and capital cost compared to individual actions. Establishing a decarbonisation trajectory for an industrial cluster requires a methodical approach using a techno-economic evaluation primarily based on the CAC curve. This entails integrating process and energy modelling, as well as including risk factors and capital costs. Finally, an orchestrator must initiate and co-ordinate the journey after setting the scene with preliminary work.

> **"Challenges of cluster decarbonisation are similar to those of individual sites. However, the complexity and divided ownership pose additional challenges"**

Part 2 of the study will continue to examine the questions related to trust that arise when decarbonisation trajectories for industrial clusters are implemented. Part 3 will discuss the benefits obtained from continuous real-time optimisation after the decarbonisation measures have been put into place.

VIEW REFERENCES

Joris Mertens
joris.mertens@kbc.global