SECTORAL DECARBONISATION: A SYSTEMS approach for cement and steel

The transition to a low-carbon future is under way in various industrial sectors. Shell India has started a journey, based on shared ambitions of decarbonisation and energy transition, to develop, deliver and implement low-carbon pathways in collaboration with customers from core industrial sectors in India. Irrespective of the chosen decarbonisation pathway, it is apparent that there is a clear need for decarbonisation of the end-to-end value chain. This requires an integrated view and understanding of a well-defined “system” that often extends beyond the premises of a plant or factory. A systems-design approach and associated system-level models have been developed and implemented to create decarbonisation road maps and explore decarbonisation pathways for the cement and steel manufacturing sectors.

The challenge
The need for decarbonisation to control climate change cannot be overemphasised. It is also important to emphasise the need for action at scale to control, reduce and offset carbon emissions. This is imperative to avoid irreversible climate change and to stay within the targets set by the Paris Agreement. Industrial companies emit just under a third of global greenhouse gas emissions, 90% of which are carbon dioxide. Between 1990 and 2014, industrial greenhouse gas emissions increased by 70% and there is no change in the trend, largely because of increasing demand in consumption driven by increasing numbers of middle-class consumers and rapid urbanisation. Industrial sites have long lifetimes, so retrofitting, upgrading or replacing these facilities to reduce carbon emissions requires extensive planning and investment. Additionally, the minerals, metals, chemicals and power sectors are hard to abate owing to their relatively high share of emissions from feedstocks, fuels and high heat requirements.

Decarbonising the industrial sector is technically possible, even with its engineering challenges and economic hurdles. The transition to a low-carbon future is ongoing and will embrace all sectors of economic activity, thereby creating new risks and opportunities. It is also important to account for the availability of niche technologies through innovation breakthroughs, rapid cost reductions in renewable energy and the availability of digital technologies to improve productivity, tracking and safety. The Energy and Resources Institute and Shell have created a detailed scenario sketch to explore the energy transition in the context of the ongoing development of the Indian economy [Ref 1]. Aligned to Shell’s climate ambitions, Shell India is focusing on India’s industrial sectors and has started a journey to develop, deliver and implement low-carbon pathways in collaboration with customers from core industrial sectors.

Sectoral decarbonisation
Implementing a lower-carbon future is a fantastic opportunity for Shell India to build additional internal capacity and capabilities and to create new global business models. These will help to drive the production of energy and carbon management solutions to meet the emerging needs of the regional and industrial sectors. Two industries ripe for change are cement and steel manufacturing.

India is the second-largest producer of cement in the world, with huge growth potential. National initiatives such as smart cities will need significant new infrastructure and are expected to provide a major boost to the sector. The Indian cement industry is forward-looking and has been proactive in recent years in significantly improving its efficiency and reducing its carbon intensity.

India was also the world’s second-largest steel producer in 2019. The growth in the Indian steel sector has been driven by the domestic availability of raw materials and cost-effective labour. There is a huge potential for growth in the Indian steel sector, driven by the expected demand increase in the infrastructure, construction, automobile and railways sectors.
The Indian steel industry is modern and forward-looking and has continuously upgraded brownfield plants to higher efficiency levels.

The eagerness and readiness of India’s industries to change are evident from the published decarbonisation goals of several of the major players and early adopters in each of the industrial sectors. As different companies and sectors determine their paths to decarbonisation, it is increasingly apparent there is a need for decarbonisation of the end-to-end value chain. Because each plant and factory depends on elements outside its control, success requires an integrated view of the entire value chain system and an inherent ability to adapt to varying environments.

This approach is comprehensively covered by the three emission scopes the Shell team has used as the basis of its work. Scope 1 includes direct emissions from owned or controlled sources. Scope 2 covers indirect emissions from the generation of purchased electricity, steam, heating and cooling consumed by the company. Scope 3 includes all other indirect emissions in the value chain. Addressing all these emissions in an efficient and insightful way needs a systems-design approach: a methodical approach for designing, commissioning, managing, operating, maintaining and retiring a system.

Systems design and natural teams
The Shell team knew it was entering uncharted territory when it first approached customers in the cement and steel industries. Success would require quick understanding of the complexity of these sectors, dealing with loosely defined problem statements and remaining flexible within an ever-changing environment. The tenets of the systemic approach were embedded in customer intimacy and a strong learner mindset. Careful attention was paid to the customers’ challenges and natural teams were created by combining Shell and customer experts at project inception. The team members aimed to work together seamlessly on a decarbonisation path, despite diversity in backgrounds, approaches, organisations and time zones.

The first step was to learn a customer’s manufacturing process and to gather relevant contextual data. This helped in creating system (flow) diagrams so that stakeholders could visualise a cement or a steel plant as a full “system”: Figure 1 shows examples. Through this shared understanding, the teams defined what was in and what was out of scope, key emission drivers and the main areas of focus. Joint workshops followed to ensure that the customer challenges were clearly articulated and that the pain points and levers to decarbonisation were clearly understood.

A set of focus solution themes was identified for subsequent brainstorming sessions. The resulting ideas were ranked, categorised and organised to construct a tentative road map that laid out potential pathways to achieving the decarbonisation goals. Being able to see the path forward was exciting, but the road map was highly qualitative at this stage: it was based on

**Systems design in context**
A system can be defined as a collection of elements that together produce an outcome unachievable by any of the single elements on their own. Systems design and systems engineering cope with the complexity of multiple elements and their interactions, help to avoid omissions and invalid assumptions, and can efficiently produce robust insights and outcomes. This approach provides a holistic understanding of the problem/opportunity space, a view of possible scenarios and traceability of the design intent and design changes of the elements, interfaces and interdependencies.

Systems design provides a science-based approach to address the complex problem of decarbonisation. It is a logical pathway to a practicable, comprehensive approach to defining a system of interest (an engineering entity or an end-to-end value chain, etc.) and evaluating it from a multiple-degrees-of-freedom perspective. System-level models are powerful tools in the systems-design toolbox: they enable reliance on a single source of truth that can be used to identify or filter pathway options to decarbonisation targets.

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**FIGURE 1**
Flow diagrams of the high-level (a) cement- and (b) steel-manufacturing processes.
FIGURE 2
System-level model developmental phases.

Starting with the system flow diagrams, the team superimposed equations that quantitively described the behaviour of the cement or steel plant and validated these behaviours against plant data. This prediction tool gave the opportunity to quantify different scenarios and assess the high-level impacts on costs, emissions and energy demands for potential future states of the plant.

For cement, the models asked, for example, “What would the impact be on the key performance indicators if the plant were to switch from petroleum coke fuel and coal-based electricity to a biomass fuel and renewable energy? What if you added an amine-based carbon capture system? What would the impact be if the plant switched to a new cement chemistry that used less clinker? How would that affect the key performance indicators?” There are endless potential questions like these and endless combinations of feedstocks and technologies that are theoretically feasible.

Although cement plants and cement manufacturing are largely consistent worldwide, the steel-making process is highly variable. For example, natural gas availability can lead to major architectural decisions: “Does it make sense to keep using existing assets built for a certain process, say, the blast furnace–basic oxygen furnace route, or would it be better to switch to a completely new process such as a direct reduced iron, electric arc furnace? At what point should these changes be made to ensure success in achieving both medium- and long-term decarbonisation goals?”

The system model can adapt to guide these types of decisions and influence what the road map should look like. The team used the tool and methodology to explore a broad solution space and to evaluate hundreds of thousands of different scenarios. The results showed what technologies should be deployed as a “bundle” to fully realise their value, what solutions were appealing but needed significant cost reduction to become economically viable and what options were mature enough to be piloted as soon as possible. Ultimately, this helped to refine the decarbonisation road maps and to clearly understand the next actions for proving or disproving the assumptions.

This approach resonated well with the customers, who could finally leverage a system-level quantitative tool to navigate through the complexity and uncertainty of decarbonisation options. The tool became a catalyst to convince the team that there was a need for an integrated solution space that could be conceived with systems design and Shell’s unique and differentiated systems engineering capability.

**System-level models**

System-level modelling is best managed by starting simple with a set of clear questions to answer, as it is easy to become overwhelmed by all the possible technologies and scenarios, especially during the early stages of analysis. The Shell strategy is to start at a high level and to introduce increasing fidelity and complexity once the questions become more focused, intricate and interdependent (Figure 2). Sometimes, this means adding layers to the baseline models and letting the original model grow in size and complexity. At other times, it means switching from an Excel-based tool to a more multifunctional modelling platform.

The system-modelling approach is a way to move the conversation from abstract and subjective to quantitative, with more objective discussions and decision-making. Using the model as a single source of truth, which all participants can always reference, keeps the discussions, explorations and evaluations objective and on track against a common baseline. This process facilitates a reasonable and healthy debate on varied approaches while the model keeps the dialogue grounded in fact. This system-modelling approach is a differentiator for Shell in energy and carbon management. Rather than pushing point solutions, Shell strives to discover integrated solutions grounded in quantitative analysis.

During the initial stages of working with a model, there is more interest in identifying the wrong answers (or, infeasible and/or irrelevant design space) so that they can be promptly eliminated from the focus and scope. Initial questions could include, “What are the viable fuel feedstocks and/or technologies that could help to meet the goals of the customer?” and “What carbon penalties or subsidies would make technologies competitive?” As the viable solutions are downselected, the model can be queried for more detailed questions, such as, “How would these new feedstocks and technologies affect the full system and interactions between its various parts?” and “What needs to change in the system to enable these solutions?”
As the model becomes more complex and detailed, the final questions could target technocommercial details, for example, “How can the system be optimised in real time and meaningfully capture the real-world variations and variabilities for one or more objectives?” Answering the final questions would be daunting and overwhelming if every possible solution set from the start of the journey had to be considered. Incremental and phased progression provides manageable steps to understanding complex systems and answering questions for discovering decarbonisation vectors.

The models are based on first principles and are deterministic in nature: they use reasonable assumptions for mass and energy balances and plant manufacturing parameters and emissions. Some level of stochastic variability has been built in for variable input parameters such as carbon pricing, taxes and commodity pricing of conventional and renewable energy. Once developed, the model outputs are validated against plant data to ensure acceptable levels of predictability and confidence for key output parameters relating to carbon reduction.

**Illustrations of decarbonisation road maps**

**Cement sector**

The starting raw materials for cement manufacturing are limestone and clay, which are fired in a rotating kiln at about 1,500°C. This causes the physical bonds to break and results in a dark grey, lumpy and nodular material called clinker. The clinker is mixed with other additives such as gypsum, fly ash and slag, and then ground in large vertical rolling mills to mix all the ingredients into the fine, light grey powder known as cement. The cement is mixed with water to make mortar and then with aggregate such sand or gravel to make concrete.

Close to 90% of carbon emissions in cement manufacturing are from the kiln and preheater operations (Figure 3). Of these, 60% are a direct result of the thermal decomposition of limestone that occurs between the preheater and the rotary kiln. The remaining 30% of the emissions are due to the combustion of carbonaceous fuels such as petroleum coke that must be burned in the kiln at a high temperature to thermally decompose the limestone and form clinker.

For the cement sector, the Shell team used the system modelling approach to drive discussions both internally and externally. First, they developed an Excel-based model to characterise the cement manufacturing process in high-level terms. Aspects such as electrical and thermal energy demands and related emissions, and process emission sources such as calcination and organic carbon contributions were considered. The team then layered in carbon capture technologies and considered the associated costs and energy demands. This scenario evaluation tool was used to assess the high-level impacts on costs, emissions and energy demands for various potential future states or scenarios of plant operations. There were many possible questions and feasible combinations of feedstocks and technologies.

This effort started by using literature and publicly available data sources. Internal discussions and critiques got the model to a level of maturity at which the team had reasonable confidence in it. They periodically reviewed the model with customers to get their direct feedback. These discussions enabled adjustment and refining of...
the tool for better reflection of plant operations mapped and validated against plant data.

Once the model was refined using validated plant data, the team used the tool to perform trade-space analyses. Unique plant configurations were evaluated and plotted against cost and carbon intensity. Clusters and Pareto frontiers emerged that indicated generally where different groups of solutions existed for these two metrics (Figure 4). Other clusters included hydrocarbon fuels with and without carbon capture, as well as hydrogen hybrid fuel mixes with and without carbon capture.

Interesting observations included that:
- hydrogen fuels without carbon capture will not solve the problem. This may seem obvious given the emission contributions from the calcination process but was reinforced through the model analysis.
- hydrogen costs need to reduce significantly to play a meaningful role in the decarbonisation road map. This fact was not surprising, as hydrogen was being compared against petroleum coke fuel, which is inexpensive in comparison, but it was accentuated and quantified using the model outputs.
- electric intensive carbon capture technologies such as oxy-fuel combustion (instead of air-fuel combustion) will not help much unless electricity production is simultaneously decarbonised.

The team likes to think of this scenario evaluation tool as an instrument for enabling directional or vectoral choices. It is a tool that enables rapid incorporation of alternate fuels, feedstocks or technologies and evaluation of whether they are impactful. From there, it is possible to focus on the items that show merit and build more complex tools to answer newer component interaction questions. Using the model helped in developing several potential decarbonisation pathways based on the scenarios that scored well in the concept downselect phase.

This is not to say that no other options were considered or that these are “the” scenarios, but they do represent viable pathways for achieving carbon negativity in the cement manufacturing process while meeting the industry’s intermediate goals. The scenarios are not necessarily mutually exclusive and may be localised depending on certain constraints, for example, the availability of fuels at a specific plant location. Each scenario represents an approach with varying levels of risk and technology maturity, supported by a cost–benefit analysis and a tentative timeline to realisation. The scenarios prioritised for further engagement had finer levels of granularity to show relevance, realisability and readiness for implementation. These scenarios were presented to the customer through a virtual workshop at which they identified their preferred pathways and/or configurations, thus, ultimately, defining their decarbonisation road map.

Iron and steel sector
The steel-making process starts with heating crushed or pelletised iron ore with coke in a blast furnace at a temperature of about 1,800°C in the presence of air. If available, scrap steel can be added as a raw material to the blast furnace. At this sort of temperature, the oxides of iron are reduced by the coke as carbon dioxide and pig
Iron is formed. The resulting pig iron has some inherently bonded carbon due to the ore reduction reaction in the blast furnace. To make steel, it is necessary to reduce this carbon content by combining the pig iron with additional scrap steel in a basic oxygen furnace. The carbon is oxidised in the presence of oxygen. Adding limestone helps to remove other impurities, such as silica, as slag. Varying percentages of manganese, nickel, chromium, carbon and vanadium are added to make different grades of steel, which can be finished to bars, billets, blooms, tubes and coils.

Unlike the cement-making process, in which most emissions are process related, steel manufacturing has multiple sources of carbon emissions (Figure 5). Raw material preparation and iron making in the blast furnace each account for about 33% of the emissions; the remaining emissions come from energy generation, steel making and the finishing processes.

The system level model makes high-level abstractions of steel manufacturing and captures the complex relationships and interactions that occur between them. The computational model aims to capture enough details to help make well-informed decisions. It also helps in understanding the potential consequences of technology and other solution choices on decarbonisation metrics that include carbon intensity and differential specific costs for alternate fuels, process modifications and technology options.

The bases of the model are the major process blocks and the associated energy and mass flows that define the relationships between inputs and outputs (Figure 6). The model is intended to be a high-level plant assessment tool and therefore uses plant level aggregation for spatial scale and annual basis for timescale. To make the plant models more representative of real steel plants, actual energy and mass flow data are incorporated to define the process-level input–output relationships, while the mathematical formulation within the model takes care of the complex interactions. Similarly to the cement-sector model, the steel model was also developed in close collaboration with a sectoral customer to ensure that the assumptions and simplifications were appropriate for the intended use cases. Actual mass and energy flow data from various plants were used for the model development and validation.

The steel system model’s primary purpose is to perform high-level assessments of technology concepts to identify and screen promising options that would be efficient in reducing carbon intensity at a manageable differential cost, especially in the near term. It aims to capture the interactions between various concepts and identify the most synergetic and integrated solution suite. The model is amenable to sensitivity studies in order to identify the impact of changes in inputs on output metrics and the robustness of a concept’s performance. The scenario analysis model is meant as a high-level assessment to capture rough estimates of how vectoral...
concepts affect metrics and not yet to provide any in-depth optimisation of plant and/or subsystem operations. The costs are modelled on a differential basis to identify the incremental changes in costs when comparing potential technology concepts. Detailed accounting costs have not yet been modelled.

**Figure 7** illustrates a specific trade-space outcome (Pareto frontier on cost versus carbon intensity, Figure 7(a)) and the impact on carbon intensity for a subset of combinations of technology choices and process levers against the baseline (Figure 7(b), with the baseline case being the left-most column).

**Conclusions and future scope**

Systems design provides a science-based approach to addressing the complex problem of decarbonisation with Shell customers. Through a data-driven approach, systems design helps to align all the stakeholders to a common view and ensures everyone is working synergistically on solving the same problem. It enables the team to make the right decisions quickly and objectively, thereby increasing execution efficiency and minimising rework.

System-level models are powerful tools in the systems-design toolbox: they enable reliance on a single source of truth that can be used to identify or filter meaningful pathway options to decarbonisation targets. During the implementation phase, the models developed for Shell customers in the steel and cement industry are expected to provide a framework to identify key assumptions that will be foundational to the successful execution of a decarbonisation plan. The framework will enable scenarios to be tested early in the journey, strengthen confidence in the resulting decarbonisation road map and progressively increase its fidelity.

In the future, the foundational work on building models for steel and cement customers in India can be leveraged to cover an increasing breadth of unique customer needs and geographies. Further, as the existing partnerships strengthen during the execution phase and new data become available,
the refined understanding of the problems and solutions can be used to grow the models into higher-fidelity tools. These advanced tools will ultimately be used to optimise future solutions and deploy them in increasingly attractive and competitive forms.

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AUTHORS
Subhrajit Dey is the technology leader of energy and carbon management, Shell India Markets Pvt. Ltd. He has more than 20 years of industrial experience in delivering energy-related technology innovation, business solutions and developing sustainable organisational capabilities. His roles have spanned technology and people leadership and programme management. Subhrajit has a master's degree in aerospace engineering from the Indian Institute of Science.

Upendra Rao is the systems integration team lead, Shell TechWorks. He leads the systems integration team and champions the use of systems engineering principles and tool sets to help solve complex problems. Upendra has extensive experience in hydrogen fuel cell development. He has a master's degree in chemical engineering from the Illinois Institute of Technology and an MBA from Carnegie Mellon University, both in the USA.

Amedeo Conti is head of systems, Shell TechWorks, and leads a team that embraces systems engineering to help Shell and TechWorks make high-quality decisions faster. He has experience in structural engineering and technology, people leadership and strategy, product and business development for hydrogen fuel cell development. Amedeo has a master's degree in mechanical engineering from Politecnico di Milano, Italy.