Preface

Hydrogen Supply Chains: Design, Deployment, and Operation

Hydrogen produced from renewable sources and used in fuel cells for both mobile and stationary applications constitutes a very promising energy carrier for the energy transition. The introduction to the market of new propulsion systems, such as the fuel cell electric vehicle (FCEV), can be one alternative to treat problems, such as energy security, urban air quality, and global warming potential. Yet, the cost of hydrogen is still considered prohibitive compared to the fossil fuels used in the transportation system, even if the development of some technologies associated with hydrogen has improved its competitiveness.

A key point in the development of hydrogen supply chains (HSC) is the demonstration of the feasibility of their infrastructure, while many technical, economic, and social obstacles must be overcome. Some strategic roadmaps have been regularly published about the energy potentialities of hydrogen at continental (for instance, European), national, and regional levels. Their main objective is to evaluate some industrial, technological, environmental, and social issues and to identify the main obstacles associated with the hydrogen economy. The literature review of recent dedicated scientific publications also agrees on the need to develop systemic studies in order to demonstrate the feasibility of the sector and to validate the techno-economic interest in the production of hydrogen produced from renewable sources.

A challenging and motivating issue is that the pathway that can be followed to develop a hydrogen economy is very flexible because many energy sources, production processes, and transportation and storage modes exist. Hydrogen can favor the connection of different energy sectors and energy transmission and distribution networks, thus enhancing the operational flexibility of future low-carbon energy systems.

The purpose of this book is to consider the interconnection of the different items contributing to the hydrogen supply chain (HSC) and to explore them

from different angles, including techno-economic, environmental, and the safety and social aspects.

The design of an HSC for fuel use can be viewed as a framework considering different levels of scale (for instance national and regional scales), combining multiple energy sources with various production and storage technologies, while considering the transportation modes to link hydrogen demand to its supply involving multiple uses. Particular emphasis is devoted to the multiobjective formulation in which cost, environmental impact, and safety must be simultaneously taken into account at the early design stage.

It must be emphasized that the scope of supply chains is classically addressed in the industrial engineering field. Yet the objective here is to focus on the specific features of hydrogen supply chain management in the context of the integration of hydrogen energy systems in the overall energy system as an important and complex subject.

The ambition of the book is to provide guidelines that could be followed to develop a hydrogen supply chain, leading to a reference hydrogen energy system architecture that can be used for energy analysis, modeling, and integration for a subsequent HSC implementation, while taking into account all stakeholder perspectives and convincing policy makers. The efficiency of the integration is strongly related to the search for optimum pathways for hydrogen supply, with an advanced knowledge of the supply chain components for energy modeling purposes.

Our goal is to provide a concise overview of the methods and tools that can be used for the deployment, design, and operation of the HSC. This necessarily means that we cannot cover every possible hydrogen pathway, but we have tried to provide the basics that are needed by engineers, managers, engineering students (MSc), and researchers (PhD, for instance) in various fields, such as Process Systems Engineering, Energy Engineering, Industrial Engineering, and Sustainable Engineering. We have tried to capture both the common threads and the diversity, being aware that the originality of a hydrogen supply chain comes from the fact that there is no unique supply chain, so that it is difficult to embed in one generic formulation all the various possibilities that may be encountered, as the design of the supply chain may vary according to the target in view.

Our book is divided into two parts.

PART I—EXPLORING THE CHALLENGES AND SCALES OF HSC DESIGN, DEPLOYMENT, AND OPERATION

Chapter 1: Hydrogen as a Pillar of the Energy Transition

This introductory chapter is devoted to the exploration of the major roles that hydrogen is likely to play in the economy, with a specific focus on decarbonization. The concept of Power-to-Gas used in hydrogen supply chains is presented. The vision that is laid out is based on a systemic view of the potential of hydrogen in the energy system, in particular for mobility purposes.

Chapter 2: Hydrogen Supply Chain Design: Key Technological Components and Sustainable Assessment

The objective of this chapter is to present the concept of the hydrogen supply chain and its main activities, including multiple sources/multiple uses, production, storage, transportation and distribution, multiples stakeholders, multiperiod strategies in a context of uncertainty (for instance demand). The criteria to be taken into account in a sustainable development context are also highlighted.

The pillars of the HSC supply chain – production, storage, and distribution – are explored in the three following chapters, which will present hydrogen production processes at various scales from macroscopic to process scale, as well as state-of-the art reviews.

Chapter 3: Assessment of Selected Hydrogen Supply Chains—Factors Determining the Overall GHG Emissions

This chapter analyzes different hydrogen production options and their respective transport needs from an environmental viewpoint.

Chapter 4: Hydrogen Production From Biogas Reforming: An Overview on Steam Reforming, Dry Reforming, Dual Reforming, and Tri-reforming of Methane

At a more local and operational viewpoint, this chapter presents a case study of green hydrogen production from biogas as a renewable resource using a multistep process, including mainly biogas reforming, water-gas-shift reaction, and hydrogen separation. It is focused on different methane reforming processes: steam reforming, dry reforming, dual reforming, and tri-reforming. This case study is particularly interesting from a process engineering viewpoint because the methodological aspects are explored for each process, encompassing thermodynamic equilibrium, process at industrial scale or research laboratory development, kinetic models, and mechanistic study.

Hydrogen storage, along with distribution, is a key technology associated with the wide use of hydrogen. Both of these two group technologies seem to be the most limiting factors, currently and in the near future, to the deployment of hydrogen in the energy system. This is the core of the two following chapters.

Chapter 5: Hydrogen Storage for Mobile Application—Technologies and Their Assessment

The various storage technologies and concepts that have been developed to date are presented in this chapter: high-pressure storage tanks, storage as liquid hydrogen, and storage of the hydrogen gas in metal hydride. Other options, such

as hydrogen storage for mobile applications, such as liquid organic hydrogen carriers (LOHC), activated carbon, Metal-Organic-Frameworks (MOFs), and others, are also discussed.

Chapter 6: Lowering Energy Spending Together With Compression, Storage, and Transportation Costs for Hydrogen Distribution in the Early Market

The optimization of cost and energy consumption for compression, transportation, and storage of hydrogen for vehicle refueling in the current hydrogen emerging market is addressed in this chapter by considering a recurrent issue in hydrogen supply chain development, that is, the location of a refueling station on a hydrogen production site and the case of a production unit supplying hydrogen to several distant refueling stations.

A HSC is globally viewed as demand-driven and hydrogen has many applications in the energy market, for example, direct use in an internal combustion engine, replacing the need for automotive gasoline, use in fuel cells to create electricity, use to power and heat buildings, alternative to natural gas in its application to heating and cooling homes, interest in hydrogen for the power-to-gas market, etc.

Chapter 7: Hydrogen Applications: Overview of the Key Economic Issues and Perspectives

The chapter explores the large range of potential applications of hydrogen from industry to the transport sector, currently and in the longer term. For each of these applications, the potential for economic competitiveness is discussed by highlighting the main drivers and variables.

Chapter 8: Social Aspects of H_2 Supply Chains

The deployment of a hydrogen economy is not without trials and controversies, doubts, and value oppositions. Using hydrogen as energy storage for renewables is particularly sound in an island context. The Corsican PV-Hydrogen MYRTE Platform serves here as a test bench for investigating the close links between technical aspects and political obligations, and the role of stakeholders.

Chapter 9: Power-to-Gas—Concepts, Demonstration and Prospects

In this vision, hydrogen from electrical energy via electrolysis is viewed as the first possible end-product of the so-called Power-to-Gas process chain or can be further converted to synthetic methane via methanation, a process requiring the feed-in of CO_2. The potentials, opportunities, and limitations of PtG are presented in this chapter.

PART II—EXPLORING METHODS AND TOOLS FOR HSC DESIGN, DEPLOYMENT, AND OPERATION

Methods and tools that can be selected to develop the methodology of the optimal design of a hydrogen supply chain are proposed, as well as their performance drivers and metrics (economic, environmental, societal). They are illustrated by significant case studies to show their large range of potential application.

Chapter 10: Methods and Tools for Hydrogen Supply Chain Design

This chapter presents the methods and tools classically used for hydrogen supply chain (HSC) design, generally involving optimization strategies. The most current trend is based on multiobjective formulations. Decision-aid methods to search for tradeoff solutions are often used. We also examine how the HSC design optimization framework can be linked with geographic information systems (GIS).

Chapter 11: Multiobjective Life Cycle Optimization of Hydrogen Supply Chains

The formulation of the design of hydrogen networks as a mixed-integer linear programming (MILP) problem is proposed in this chapter, including environmental objectives along with economic ones. From these optimal designs, stakeholders must select the one that best matches their preferences, considering the applicable legislation and technical, economic, and environmental constraints. The case study of the future supply chain (SC) for vehicle use in the UK is considered.

In addition to PtG supply chains, it must not be forgotten that hydrogen has been an increasingly important component of refining in the process industries, particularly in view of the increased demand for clean fuels. Refinery hydrogen networks typically interconnect many producers, consumers, and purification units with different pressures, purities, and operating objectives. This kind of gas network is the core of the two following chapters, dedicated to the formulation of the operational optimization model of a hydrogen pipeline network.

Chapter 12: Engineering Robust Strategy for Solving Optimization Problems of Refinery Hydrogen System

A robust engineering strategy that has been applied to hydrogen pipeline networks of a large-scale refinery has been developed for optimal scheduling of the hydrogen system to reduce energy cost and carbon emissions in refineries.

Chapter 13: Optimal Design of Refinery Hydrogen System With Purification Unit

In this chapter, both the pinch technique and mathematical programming approaches are introduced for the synthesis of a hydrogen network with a purification unit.

Chapter 14: Metamodeling of Hydrogen Supply Chains: A Programmable Structure Based Representation

Besides the well-developed mathematical programming–based optimization methods, the design and operation of these large-scale, long-term processes might also optionally require easily extensible, generic dynamic simulation. This chapter shows how the programmable structure of process models can be generated from the description of a process network (optionally geographically determined and multiscale) and from two general functional metaprototypes.

Chapter 15: Life Cycle Assessment of Hydrogen Supply Chain—A Case Study for Japanese Automotive Use

One of the supporting methodologies for environmental impact evaluation is life cycle assessment (LCA). The idea of integrating LCA into supply chains has received increased interest. A "Well-to-Wheel" (WtW) analysis in the Japanese context was conducted to understand the role of hydrogen in reducing greenhouse gas (GHG) emissions in the vehicle transport sector from a life cycle perspective.

Chapter 16: Risk Analysis of Complex Hydrogen Supply Chains

This chapter focuses on methods to assess safety risks in the future hydrogen-based infrastructure. The development of new large-scale infrastructure is viewed as a gradual procedure requiring different decision support tools, including cost-benefit assessments, sustainability assessments, optimization of supply chains, the best placement of buildings and process equipment in a growing market, and, last but not least, safety risk assessment and management.

Catherine Azzaro-Pantel
INP Toulouse, ENSIACET
1 August 2018