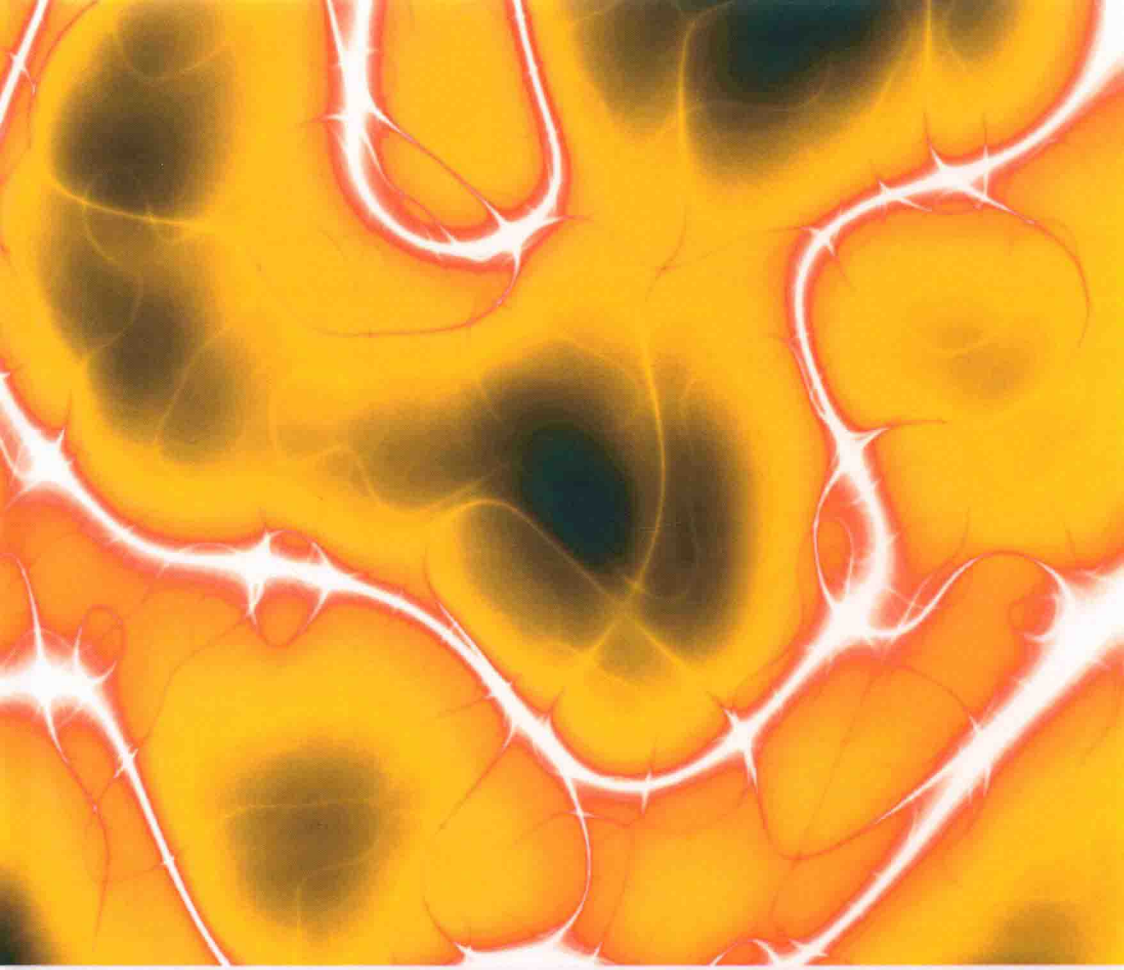

From Pinch Methodology to Pinch–Exergy Integration of Flexible Systems

Assaad Zoughaib

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Current changes to the energy market, as well as an ambition to achieve decarbonation and highly energy efficient systems, will lead to a fundamental change in the way in which energy systems are designed and managed. In particular, the growth of renewable and renewed energy will introduce a level of design and management complexity with a greater need for efficient energy storage.

Beginning with the earliest methodologies (pinch), this book explores the methodology and tools necessary for the design of flexible energy efficient systems. In addition to studying the related literature, the author details original developments where exergy consumption is introduced as an objective function to minimize in mathematical programming models for both continuous and batch processes.

Most of these developments were made in the Center for Energy Efficiency of Systems at Mines ParisTech and reported in PhD dissertations and published articles. The whole methodology is implemented in the open source CERES platform.

Assaad Zoughaib is Professor at Mines ParisTech in France, and leader of the Thermodynamics of Systems research group. His research focuses on systemic methodologies for the energy efficiency of systems and the development of innovative high efficiency energy conversion systems.

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Thermodynamics – Energy, Environment, Economy Set

coordinated by
Michel Feidt

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From Pinch Methodology to Pinch–Exergy Integration of Flexible Systems

Foreword

This book proposes a novel vision of thermodynamics as applied to the engineering of systems and processes subject to energy and mass transfer and conversion.

The methodology presented in this book aids in the design of systems and processes industry needs with improved sustainability and efficiency while considering the practical and economical feasibility.

This book is, therefore, at the heart of the *Thermodynamics – Energy, Environment, Economy* Set.

It answers a need for students at the bachelor level but also for engineers and researchers.

This book presents the main research work lead by the author within the Department of Energy and Processes (DEP) at Mines ParisTech. I had the chance to follow and participate in part of these works, always while working closely with the industry.

The author already teaches about these new methodologies in many of his classes in different Master programs which testimony the actual character of these works and their industrial applicability.

Without a doubt, this work will be followed by many developments and perspectives, the possibilities of which are discussed in the Conclusion of this book.

I sincerely hope that this work finds the success it deserves!

Michael FEIDT
Emeritus Professor
University of Lorraine, France

Introduction, Context and Motivations

In this chapter, contextual elements are presented to show the link between world systemic constraints (demographic and economic growths), resource consumption (focusing mainly on energy) and environmental issues (climate change and upcoming resources scarcity) related to current production and consumption patterns.

This leads to an anticipated situation that is not sustainable unless the world changes its paradigms in terms of energy supply and consumption. Energy efficiency is one of the cornerstones of energy systems and process design for the future, while their flexibility is the other, considering the future picture of the energy supply system. Indeed, the introduction of renewable and renewed energy will introduce a higher level of design and management complexities with a higher need for process flexibility and energy storage.

Starting from the earlier methodologies (pinch methodology, exergy analysis), this book tries to introduce the methodology and tools necessary for the design of energy-efficient and flexible systems.

I.1. Systemic constraints

Since the industrial revolution, the world population has grown exponentially from 1 billion around 1850 to 7.4 billion today (Figure I.1). It increases at a staggering rate of 80 million people per year. This expansion can be easily associated with technological innovations, in particular, with the rise and mastering of energy provided by fossil fuels.

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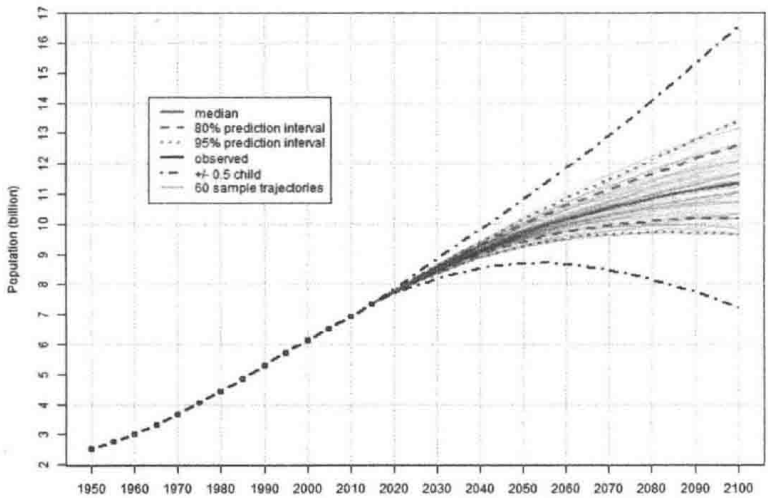

Figure I.1. *World's population since the industrial evolution and its possible variations [UNI 15]. For a color version of this figure, see www.iste.co.uk/zoughaib/pinch.zip*

It resulted in a tremendous and unprecedented period of prosperity for human civilization (Figure I.2). The exponential growth of the world's Gross Domestic Product (GDP) from the 1850s is evidence of this.

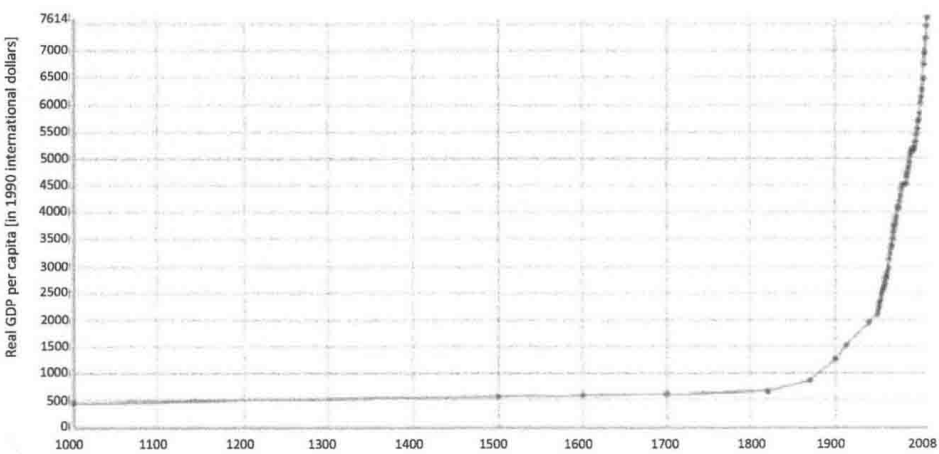

Figure I.2. *World's GDP over the last 1000 years*[1]

However, this population and economic growth has put a great and steady pressure on the environment since more and more natural resources are

1 https://ourworldindata.org/gdp-growth-over-the-last-centuries/.

consumed with an increase in waste and pollutions as a result. Indeed, in the prevailing linear economic model, resources are extracted and transformed to produce goods and services which are then consumed, producing waste that is more or less discarded back into the environment.

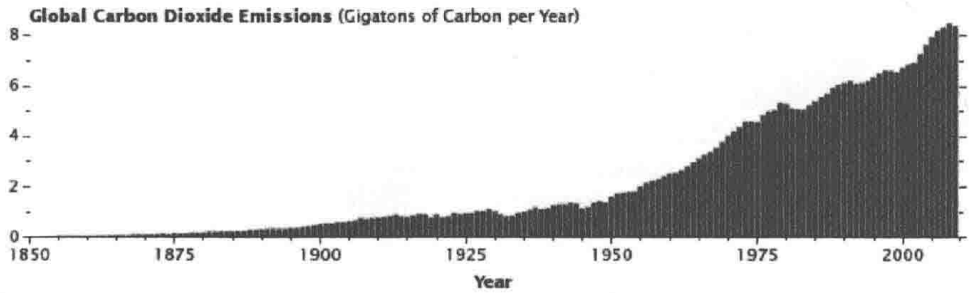

Figure I.3. *CO_2 emissions since the industrial revolution*[2]

Unfortunately, human activities have been profoundly linked to an increase in greenhouse gas emissions and pollution around the world (Figure I.3). This has resulted in dramatic changes in the climate and environment with significant consequences on human lives (natural disasters, health issues, political conflicts), which may worsen if the current conditions do not improve. Knowing that in order to limit global warming to 2°C, a maximum of CO_2 emissions of approximately 3,000 gigatonnes (Gt), of which two-thirds have already been emitted [IEA 15a], should not be exceeded. This suggests that the current economic model is not sustainable for the planet nor its inhabitants. A steadily increasing proportion of the population in developing countries (basically countries which are not OECD[3] members), particularly in China and India where one-third of the world's population lives, are demanding higher living and working standards, driven by the globalization of markets, information and culture. Therefore, building infrastructures is necessary to provide a more reliable access to food, water and energy as well as all goods and services that the modern economy of developed countries offers to its inhabitants. For that purpose, their industrial sector will consume more and more natural resources and energy (in particular fossil fuels, as shown in Figure I.4) to meet the growing demands.

2 Graph by Robert Simmon, using data from the Carbon Dioxide Information Analysis Center.

3 Organization for Economic Co-operation and Development.

The world population is expected to reach 9 billion people around 2050 (Figure I.1). More and more people will live in cities (by 2050, nearly 70% of the world population will live in urban areas [OEC 14]) and will have access to all goods that the economy can offer (cars, computers, Internet, smart phones, etc.).

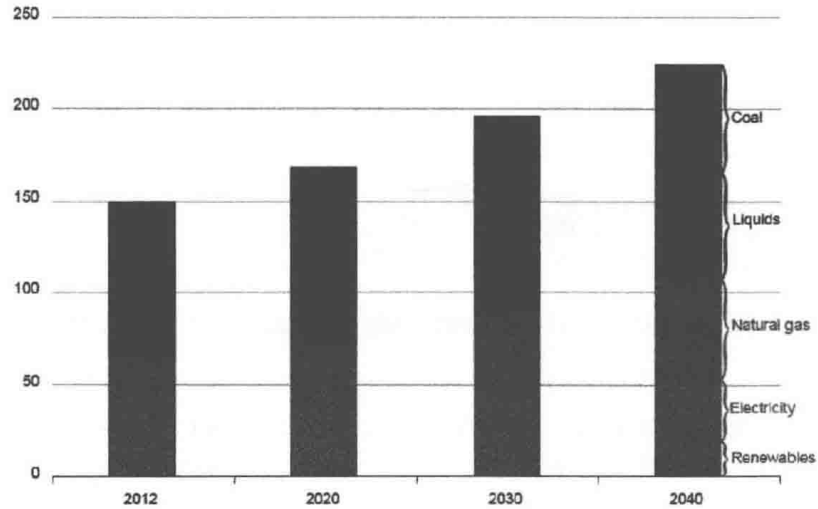

Figure I.4. *Non-OECD industrial sector energy consumption forecasts (×1015 Btu) [DOE 16]. For a color version of this figure, see www.iste.co.uk/zoughaib/pinch.zip*

This will create a strong competition for land (between agriculture, industry and housing) and resources (especially in water stress regions between drinking water for people and water necessary for manufacturing goods). Therefore, new ways of producing and consuming must be found to sustain the rising population and its needs while avoiding environmental damages and resource scarcity.

I.2. Energy consumption and production

Currently, the world consumes on average 150,000 TWh of primary energy per year. It has more than doubled over the last 40 years (Figure I.5). Fossil fuels (coal, oil, gas) represent the main energy source with 78% of the world primary energy consumption. They are also the main source of greenhouse gas (GHG) emissions.

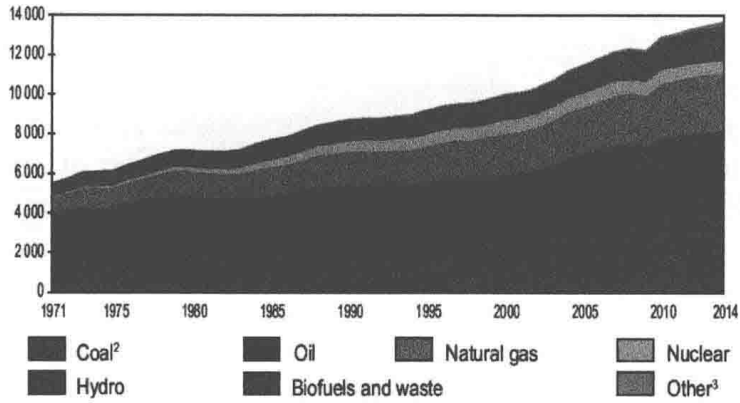

Figure I.5. *World's total primary energy consumption from 1971 to 2014 by fuel (Mtoe) [IEA 16]. For a color version of this figure, see www.iste.co.uk/zoughaib/pinch.zip*

The world final energy consumption is roughly divided between residential (20%), transport (25%) and industry (55%), mainly provided by fossil fuels [IEA 16]. As shown in Figure I.6, industrial activities account for more than 50% of world GHG emissions (32 Gt in 2014), and its share has been growing rapidly in non-OECD countries (mostly China and India) related to their economic growth. In OECD countries, relocation of industrial activities as well as measures to improve the energy efficiency have helped control the level of emissions in the last 25 years. However, the global GHG emissions have increased by about 50%.

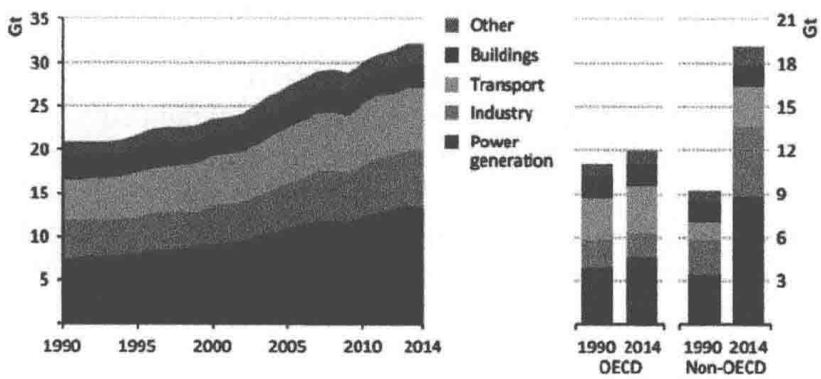

Figure I.6. *CO_2 emissions between 1990 and 2014 [IEA 15a]. For a color version of this figure, see www.iste.co.uk/zoughaib/pinch.zip*

By 2050, the world economy is expected to be four times larger than it is today [OEC 14]. Energy needs will be 80% higher than today if no changes are implemented by then, whether on technical, cultural, political, economic or social levels. Even though the part of renewable energies in the world energy mix is likely to grow faster than any other types of energy source, fossil fuels will remain the most important energy source (Figure I.7).

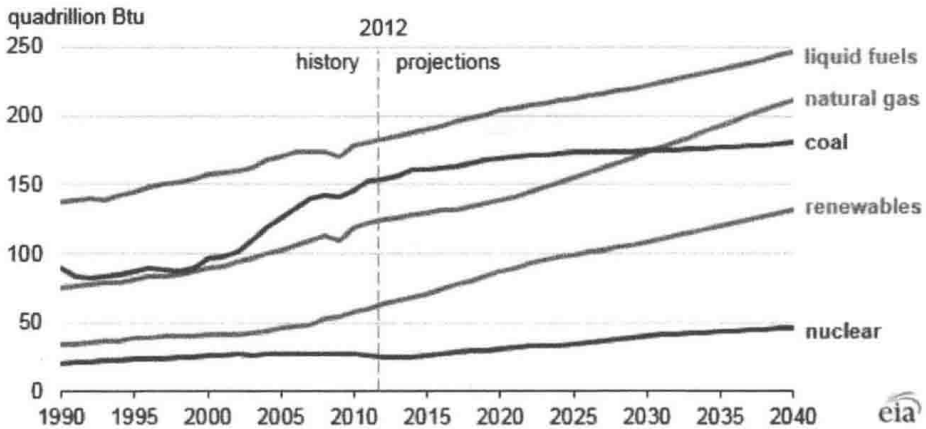

Figure I.7. *Projection of world's final energy consumption by fuel by 2040 (×1015 Btu) [DOE 16]. For a color version of this figure, see www.iste.co.uk/zoughaib/pinch.zip*

Even though their integration and management on the electrical grid remains a complex problem to be solved due to their intermittent nature, renewable energies are the future of world energy supply. One complementary solution that can help answer current environmental and economic issues would be to reduce energy needs by radically improving the efficiency of existing urban and industrial processes. Indeed, energy efficiency aims at reducing energy requirements to produce the same output. In Figure I.8, it represents approximately 40% of the total potential for GHG emission reduction. In particular, it accounts for more than two-thirds of the industry potential.

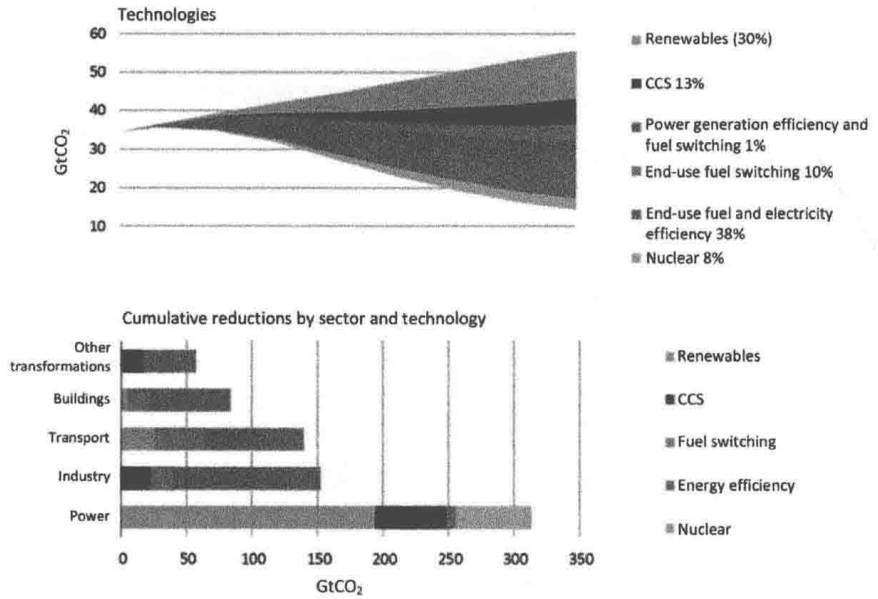

Figure I.8. *Technical solutions to limit CO_2 emissions and their potential [IEA 15b]. For a color version of this figure, see www.iste.co.uk/zoughaib/pinch.zip*

Energy efficiency has various economic advantages at different scales. For a company, it can increase product profitability and reduce the dependency towards energy suppliers. For a country, it helps avoid energy importations and controls its trade balance, and will have deep political implications for its geopolitical strategies and budget allocations (see Figure I.9).

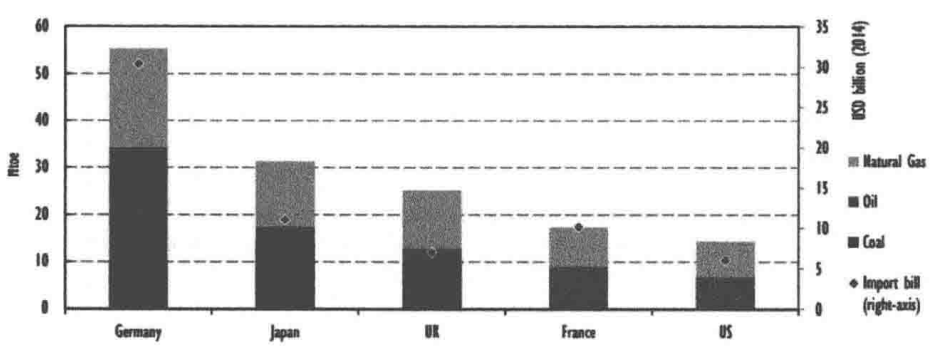

Figure I.9. *Avoided volume and value of energy imports from efficiency investments [IEA 15c]. For a color version of this figure, see www.iste.co.uk/zoughaib/pinch.zip*

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