Michel Claessens

ITER The Giant Fusion Reactor

Bringing a Sun to Earth

Second Edition

Springer

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Foreword to the First Edition

I first visited the ITER site in the autumn of 2009. There were many people working there, beavering away in temporary office buildings while their glossy new headquarters took shape nearby. People came and went: national delegations, scientists, engineers, nuclear regulators and suppliers. But up a steep bank behind those busy offices, the actual construction site where the great machine would be built was desolate. On this bleak expanse of gravel and puddles, a kilometre long and half as much wide, nothing was happening—as if a giant had built a court for pétanque, the bowls game popular across France, but no other giants had turned up to play.

It was three years on from the handshakes and backslapping that accompanied the signing of the ITER Agreement that fired the project's starting gun. Yet its new managers had decided to take another long and detailed look at the reactor's design. Tensions were running high, among its backers, who wanted more progress, among scientists, who wanted results, and among engineering companies who wanted a piece of the action. But delays proliferated and ITER seemed to be demonstrating the maxim that has always dogged fusion: that it's the energy of the future and always will be, or some variation on that theme.

Ten short years later, it's hard to imagine that desolation. The giant's sportsground is filled with countless buildings on a suitably gigantic scale, towering cranes, sprawling electrical switchyards, thousands of workers bustling about like ants, the looming edifice of the assembly hall cloaked in mirrors, and next to it, the sturdy walls of the reactor building rising slowly from a pit in the ground, soon to be ready for cranes to lift segments of the reactor into place. Project managers say construction is more than 60% complete and few now doubt that ITER will defy the maxim and the future will arrive.

People understandably complain about the ever-increasing cost of ITER and the snail's pace at which fusion is moving towards a usable energy source. But that cost is spread across 35 nations which represent more than half the world's population. The fact that those countries, some of which are politically at odds with each other, are working together so peaceably to achieve clean energy has got to be admired. As for the pace: nobody said it was going to be easy, but with global temperatures rising and glaciers and icecaps melting, the stakes could not be higher. We would be fools not to at least try to make it work.

The ITER project is epic in scale and global in extent. Yet as I've written about it over the past couple of decades I've found that, when people ask me what I'm working on, I have to explain what ITER is, what fusion is and why it's important. ITER stays resolutely below the radar of the public consciousness. I never have to provide explanations for the Hubble Space Telescope, CERN, or the International Space Station, which are projects similar in scale and importance. Yet, it could be argued that ITER has more relevance to people's lives than those other three. While the first two are awe-inspiring efforts to understand the universe and the third is a superpower vanity project, fusion has the potential to solve one of the greatest threats to humanity, our current climate crisis.

I'm sure that once ITER starts operating and begins ticking off milestones, it will regularly be in the news. But we should not wait until then to let people know of its importance. Especially in such uncertain times, it is important for people to have a reminder of what we can achieve if we work together and that, with enough determination, we can solve the challenges we face. That is why this book is so important.

London, UK
June 2019

Daniel Clery
Journalist with Science Magazine

Preface to Second Edition

The first edition of this book was published in the summer of 2019. I must say—and I know that my editor will also agree—that it has been quite successful in terms of sales, downloads and reviews. It turned out that most readers and the media were quite enthusiastic about the book. For example, I was very pleased to receive from Robert Aymar a physicist and former chair of the ITER Council who is often considered as the "father" of ITER, the following comment in late 2019: "Progress in nuclear fusion research is not often reported by the media but your book provides an excellent and comprehensive documentation, easy to read. Please receive all my congratulations! You covered all the aspects of the project—both technical and political—by providing a lot of references such as, from now on, any study on ITER cannot avoid relying on and exploiting the content of your book."

More importantly, I received and continue to receive many questions about ITER, as well as invitations to give lectures and write articles. People seem to appreciate the fact that the book provides a comprehensive account of the project's development presented in an engaging and popularised way and enriched with personal opinions, memories and anecdotes. Little by little, my book has become a reference on ITER and fusion in general—although it is not a textbook. I therefore came to the conclusion that it deserved a new edition. Indeed, in four years, a lot has happened at ITER. There has been impressive progress in building the machine which is visible from the ITER worksite and on the ITER website. At the same time, some significant new problems arose—at technical and management levels. They culminated with a public hearing on ITER at the European Parliament on February 28, 2022, where the ITER management was questioned. Clearly, my book would soon be out of date.

After a brief exchange with my editor in London, Anthony Doyle, his reaction was immediate and positive. This is, in short, the background to this second edition. I have corrected and updated all chapters of the first edition and three additional chapters give an overview of the recent advances and difficulties. As I have said before, ITER is a complex and challenging project and so will it be until the end…

Vinon-sur-Verdon, France
May 2023

Michel Claessens

Acknowledgements and Preface

I would like to express my sincere thanks to all the people—scientists, experts, government representatives, journalists and citizens like you and me—who have contributed to this book, in particular through a number of information exchanges and interviews, in the last several months or before. A special mention to Jean-Marc Ané, Carlos Alejaldre, Sylvie André, Robert Arnoux, François d'Aubert, Robert Aymar, Pietro Barabaschi, Bernard Bigot, Philippe Busquin, Ken Blackler, David Campbell, Yvan Capouet, John Carr, Daniel Clery, Laban Coblentz, Kathryn Creek, Lynne Degitz, Luo Delong, Arnaud Devred, Shishir Deshpande, Diana Diez-Canseco, Krista Dulon, Jean Durieux, Joelle Elbez-Uzan, François Genevey, Claudie Haigneré, Nick Holloway, Joel Hourtoule, Jean Jacquinot, Kijung Jung, Steven Krivit, Hubert Labourdette, Gyung-Su Lee, Paul Libeyre, Akko Maas, Osamu Motojima, Philippe Olivier, Jérôme Pamela, Annie-Laure Pequet, Hélène Philip, Thiéry Pierre, Roger Pizot, Jean-Pierre Raffarin, Iris Rona, Bettina Roselt, Ned Sauthoff, Laurent Schmieder, Takayuki Shirao, Tom Vanek, Vladimir Vlassenkov, Pascal Weil, Peter Weingart, Paul Wouters and I am sure a lot more whose names I have forgotten. I hold their contributions in high esteem, even if they are anonymous and invisible—except for me.

I am also grateful to the people who have greatly improved the quality of the second edition of this book by pointing out an impressive number of errors, inaccuracies and omissions. Great thanks in particular to Alice Whittaker, Giulia Marzetti and Elizabeth Trump, who turned the book into real English! Let me add that, despite all these valuable contributions, I take sole responsibility for the mistakes and imperfections of this book. And last but not least, I am very grateful to my wife Xuling as for several months (again), my brain was trying to confine ITER and highly energetic plasmas…

Popularising a subject like ITER is a great challenge as information about it, albeit not necessarily hidden or secret, is not always available or public. Sometimes, it is just not easy to find! For a technical, international and nuclear project such as ITER, transparency has its limits. I have therefore done my best to retrieve the right information and present it as objectively as possible, without avoiding commenting on it wherever appropriate. I am also grateful to Springer and in particular Anthony Doyle, for publishing this second and fully updated edition of my book on ITER. A final remark: the opinions expressed in this book are personal and do not in any way bind my previous employers, i.e. the European Commission or the ITER Organization, where I used to work as a science communicator.

Should you wish to be kept informed about the evolution of ITER kindly follow me on Twitter @M_Claessens or email me at michel_claessens@yahoo.fr.

Vinon-sur-Verdon, France Michel Claessens

Introduction

On November 17, 2010, in Cadarache (close to Marseille), under a Provençal sunlight and in the presence of some 400 guests, Osamu Motojima, the then Japanese Director General of ITER,[1] laid the foundation stone of the headquarters of the ITER Organization and established almost four years before to coordinate an ambitious international nuclear fusion research programme. It was indeed on November 21, 2006, that the biggest economic powers of the planet gathered in the Elysée Palace in Paris and in the presence of the French President Jacques Chirac to sign an international agreement to build the most powerful experimental nuclear fusion reactor in the world.

Freshly appointed to the post, Motojima was keen to welcome the ITER Council, the governing board of ITER comprised of high-level political representatives from the seven founding members of the project.[2] After travelling to Cadarache for this highly symbolic ceremony, the members of the Council were not shy of showing their happiness: after 22 difficult years of preparation, conceptual design and detailed planning, the project[3] was finally born. As French journalist Robert Arnoux and physicist Jean Jacquinot put

[1] Pronounced "eater". ITER is the acronym of *International Thermonuclear Experimental Reactor*. However, given that the adjectives *nuclear* and *thermonuclear* today generate much opposition and misunderstanding, the ITER promotors such as the ITER Organization and the European Commission use to explain that ITER is the Latin for the *way* (towards a new source of energy).

[2] In alphabetical order: China (People's Republic of), Europe (European Union), India, Japan, Korea (Republic of), Russia, and United States.

[3] A project is often described as a singular effort of defined duration while a programme is generally comprised of a collection of projects. The reality is a bit more complex but we consider in this book

it in 2006: "In Cadarache, along the banks of the Durance River, a dream long considered to be a chimaera, will materialise. Bringing together their knowledge and experience, physicists, engineers, technicians, and management experts from all over the world are embarking on a road to the stars. With ITER, humanity is ready to conquer fire for the second time.[4]" Now, 17 years later, the adventure continues: construction is almost complete on the site and the assembly of the machine is progressing, albeit much more slowly than foreseen.

Without a doubt, ITER is an ambitious project. The reactor under construction, which will be 10 times larger than the largest machine of its kind ever built, is only the most visible part of a gigantic international effort. Look around and you will discover, for example, a high-energy neutron source in Japan aimed at developing materials for the industrial exploitation of fusion. Another 15 more modest installations are located all over the world, preparing experiments and testing innovations and improvements for ITER. All of these are supported by phenomenal computing power provided by dozens of computers located across various high-security locations.

According to its member countries, ITER should demonstrate that hydrogen fusion, the reaction naturally occurring in the Sun and the stars, can be replicated on Earth for several minutes and produce power equal to several hundreds of millions of watts. Thus, if ITER succeeds and if the technology turns out be economically sustainable, fusion could become a new power source used on an industrial scale to produce electricity on Earth in a safe and environmentally friendly way. Fusion uses as its fuel a mix of hydrogen isotopes (deuterium, which is very abundant, and tritium, which is rare on Earth) and produces little waste. ITER will therefore produce a "green nuclear" energy, without any major drawbacks despite the production of (short-lived) radioactive waste. Although there are still unanswered technical questions such as the supply of tritium and the material for covering the reactor's inner walls, the advantages of fusion are therefore high. The seven members of ITER, who committed to build the machine together, realised this quite a while ago. By mobilising considerable resources and several 1000 people around the world, ITER is, in some respects, not so much different from Second World War's Manhattan Project, albeit in the field of peaceful scientific research. It is possible that ITER will revolutionise nuclear power forever.

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that a programme tends to involve a bigger team and to have lower levels of uncertainty. ITER is actually both.

[4] Arnoux R, Jacquinot J (2006) ITER, le chemin des étoiles? Edisud, Saint-Remy-de-Provence.

But we are not there yet. There are still areas of shadow and black spots under the fusion star. The project's difficulties are in proportion to its challenges; delays are accumulating as the first experiments will take place in 2030 at the earliest (although the ITER website still mentions 2025 as the official date), and the budget is quadruple its original size (according to the latest estimates, the construction only will cost more than EUR40 billion although, as we will see, the concept of "cost" is here meaningless). High-tech experts have been used to put these problems in perspective as this is the most complex machine ever built by humankind. Some also compare ITER to the Apollo project due to its technological sophistication and its potential to irreversibly modify both the course of history and the future of our civilisation. The seven ITER members actually represent 33 countries—more than half the global population—which have decided to work together to construct the project. ITER is among the world's largest scientific and peaceful cooperation projects. Although this is not often pointed out, ITER is a "generous" project in that the countries participating in the experiment have decided to learn together and share all the knowledge that will be developed in the framework of this huge international cooperation. This is obviously not just about science and technology, the objective is also to develop a worldwide fusion industry.

Is ITER the "star of science" whose creation has been made possible by humankind's sophisticated mastery of the laws of nature and the powers of technology? Or is it only the result of a scientific marketing operation supported by a community of researchers who managed to convince policymakers that they hold the keys to our energy future? What is ITER in the end? A revolutionary programme likely to save our civilisation or yet another expensive project aimed at impressing politicians and industrialists? At least there is unanimity on one point: since its launch the project has triggered a lot of controversy.

I am well aware of the difficulty of producing a narrative for a nonspecialist audience about such a complex subject. There is a great risk of focusing on minor details or concentrating on issues which are purely technical, perhaps even trivial. Worse, readers may suspect that this work has been written to put forward the ideas of a particular cause or even as an evangelist text. This bias is present in all books even the most "scientific" ones. From physics to biology to environment and medicine, there are abundant examples of world-renowned scholars who have, in the name of science, put forward a political opinion and/or an ideological point of view.

I fully assume this risk, although I do not see myself as an evangelistic and have no contentious issue to sort out. Nor do I claim to present a scientific book on fusion and ITER—this is very much beyond my competence. Science and technology are nowadays so specialised and compartmentalised that such a book would have to involve dozens of co-authors who would each deal with their specialty—from plasma physics to nuclear engineering and materials science, magneto-hydrodynamics, heating technology, civil engineering, computer-aided design, etc.

But ITER is a fabulous subject, especially for a science writer like me. Having devoted more than 20 years of my life to the relationship between science and society, I have followed since its inception the evolution of this incredible project situated at the interface between the research world and the energy sector. I have therefore decided to write a book for nonspecialists. I hope to contextualise the programme in its many different dimensions—historical, scientific and technical, of course, but also political, economic, human and philosophical. This small book therefore offers a snapshot of the programme and summarises what has been accomplished, without avoiding the drawbacks and issues that come along with the project. I'll also occasionally digress with some notes, personal memories and anecdotes because as had recalled the previous Director General Bernard Bigot, this exploration at the frontiers of science and technology is indeed also and maybe above all, an "extraordinary human adventure.[5]" Pushing science and technology to their limits for a noble and peaceful purpose is an endeavour that deeply pervades all of us. Transforming matter can also transform our minds and values. Some colleagues even feel a part of humanity's struggle through the centuries. In any case, it is a formidable experience, enriched by the convergence of the continents of knowledge and the rallying of cultures united by the same passion. I hope that you will share my passion.

In the following pages, we will take a look at the major milestones that accompanied the genesis of the ITER programme and discover the principles of nuclear fusion (without, however, let me reassure you right away, turning the book into a physics handbook). Then we will examine the great machine currently under construction and address the questions that most of us are asking about ITER: Why in France? Why has Europe joined with six other partners? How much will ITER cost? Who opposes the programme and why? What are the risks? How is such a complex undertaking being managed? Why is the assembly of the reactor interrupted since 2022? And finally this fundamental question, perhaps above all others: Will the ITER star ever shine?

[5] Bigot B (2016) La fusion thermonucléaire et le projet ITER. Revue de l'électricité et de l'électronique, special issue 3.

Due to the recurring delays and the exponential increase of the budget, two of the seven ITER members, specifically the United States and India, have considered withdrawing from the project. If this happened, would it mean a major delay or even the death of ITER? Some think, even within the scientific community, that fusion energy will always remain a mystical chimera. Recalling that fusion energy has been in development for over 30 years, the most sceptical state that it will always be 30 years away… A view that seems to be confirmed every day by ongoing delays.

The subject is without doubt a complex one that covers many varied topics. Therefore, this book is organised in such a way as to allow a nonlinear exploration. However, I recommend readers start with the first four chapters that describe the general context and the basics of the programme. After that, readers should feel free to pick and choose according to their desires and interests.

I like to present ITER as a living project, still under construction and in constant evolution. The downside to this point—and this is the last remark in this introduction—is that some of the information contained in this book will become obsolete even as soon as it is published. Despite days spent verifying the technical data with experts and colleagues, the publication of this book will freeze its snapshot of ITER in a way that cannot be immediately updated. But this is the price that has to be paid, dear readers, to peek behind the scenes of this enormous project and see the work of the scientific and industrial elite of the planet (Fig. 1).

ITER in Numbers[6]

23,000 tonnes. The ITER reactor ("tokamak") will weigh 23,000 tonnes which is the weight of three Eiffel Towers. Approximately, one million components and 10 million parts will be integrated into this complex machine.

400,000 tonnes. Some 400,000 tonnes of material will rest on the lower basement of the "tokamak complex," including three buildings, the 23,000-tonne machine and all its equipment. This is in total more than the weight of New York's Empire State Building.

100,000 kilometres. The 18 toroidal field coils (each 17 m high) have been wound from superconducting strands made from a niobium-tin alloy (Nb_3Sn). Some 100,000 kilometres of these strands have been fabricated by industries of six out of the seven ITER members—China, Europe, Japan, Korea, Russia and the United States. This is a record-beating production.

[6] Adapted from the ITER Organization's website: www.iter.org.

104 kilometres. The heaviest components of the ITER machine are being shipped to Fos-sur-Mer, the French harbour on the Mediterranean Sea closest to the site. Then they are transported along 104 km of specially modified road known as the "ITER itinerary." The dimensions of these components are mind-blogging: the heaviest and largest, a ring magnet manufactured in China, weighs nearly 900 tonnes including the transport vehicle and is approximately four-storey—or about 10 m high.

5000 people. Close to 5000 people work today at the headquarters of the international organisation and on the ITER worksite. As the peak of construction and assembly activity has been achieved in 2022, this number is now decreasing smoothly.

15,000 visitors per year. Since the opening of the site in 2007, more than 200,000 people have visited ITER. In groups, with family or individually, visits are possible with advance registration.[7] ITER also organises two "Open Door" days a year.

Fig. 1 Aerial view of the ITER worksite in Cadarache (close to Marseille) in March 2023. The site has a total area of 181 ha. (Left) The main warehouse that is used for the storage of the reactor parts delivered by the seven ITER members. (Top right) The headquarters of the international organisation (the building which is bent and has a dark façade). The reactor will be located in the tallest building on the platform that is surrounded by four cranes (beside what is known as the "assembly hall"). Nearly, 5000 people are currently working on the site. From ITER Organization

[7] See the page http://www.iter.org/visiting.

Contents

1

The Future of Energy

Abstract The demand for energy continues to grow in virtually every country in the world, a “natural” consequence of demographic changes, boosted by the almost universal increase in quality of life and by the development of emerging economies. The world’s energy consumption has more than doubled since 1973; it could even be tripled by the end of the century. Although the planet’s main fossil fuels—oil, natural gas and coal—are being depleted, they still provide more than 80% of the energy consumed. The pressing reality of climate change calls for a radical and urgent change in our relationship to energy. At the same time, we must develop new solutions that are as safe and environmentally friendly as possible, based on sustainable and universally available sources. Fusion energy, which reproduces physical reactions occurring in the Sun and the stars, meets these requirements. Most of the world’s scientific community is convinced that scientific and technological mastery of this energy is within reach. However, will we need fusion energy at all? Several experts argue that an energy supply based solely on renewable sources is possible by 2050. Nevertheless, despite growing investments and encouraging evolutions many experts do not envisage green energies completely supplanting all “unsustainable” sources before the end of this century. They point to physical space constraints and natural fluctuations of solar and wind energies as factors limiting the contribution that clean energies will make to global energy production. In future, energy will probably be supplied through a diverse “mix” of energy sources. Will humanity need controlled fusion to secure its energy future? Maybe, maybe not. Some Nobel laureates, like the French physicist Georges Charpak, have strongly

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criticised ITER. But some high-level government officials have different ideas. "We would be crazy not to achieve ITER," said Geneviève Fioraso, then French Minister of Research and National Education, when she inaugurated the headquarters of ITER in 2013. We will address these contradictory statements and apparently irreconcilable positions in the following chapters.

Keywords World energy consumption · Climate change · Renewable energies · Fusion

With the sword of Damocles hanging over our heads the demand for energy continues to grow in virtually every country in the world, a "natural" consequence of demographic changes, boosted by the almost universal increase in quality of life and by the development of emerging economies. The world's energy consumption has more than doubled since 1973; it could be further tripled by the end of the century. Though the planet's main fossil fuels—oil, natural gas and coal—are being depleted, they still provide more than 80% of the energy consumed. The pressing reality of climate change therefore calls for a radical and urgent change in our relationship to energy. Opinions differ on the solutions to be implemented, but there is no doubt that industrial energy production will go through a profound change in the coming decades.[1] The benefits of technology, which has given us many energy-intensive gadgets, have never been fundamentally questioned. But the public is calling on policy-makers to set clear goals regarding the protection of the planet, to propose actions at the level of individuals and to support research related to these goals.

If we are to meet our present and future energy needs and continue to grow without harming the environmental balance too much, two things are almost universally agreed: we must reduce or at the very least rationalise our energy expenditure. At the same time, we must develop new solutions that are as safe and environmentally friendly as possible, based on sustainable and universally available sources. Fusion energy, which reproduces physical reactions occurring in the Sun and the stars, meets these requirements. The majority of the world's scientific community is convinced that scientific and technological mastery of this energy is within reach. To demonstrate this, the 7 members of ITER, grouped in the international ITER Organization, decided in 2006 to build an experimental reactor in Saint-Paul-lez-Durance in the forest of

[1] Not just because oil is depleted but mainly for climate change. Also, it is too precious to be used to move cars; it should be available only for pharmaceutical and industrial exploitation.

Cadarache, which should achieve fusion energy production over at least ten minutes for the first time in history.

What Sources of Energy Are Available and How Much Do We Need?

Although humankind consumes more and more energy, we use only a small part of the power received or produced on Earth: world consumption currently accounts for only 1/10,000th of the energy received from the Sun at ground level.

According to a recent report,[2] world energy consumption, which is best measured by the total primary energy supply, was in 2021 14,212 million tonnes of oil equivalent,[3] up 54% since 1995 (see breakdown in Fig. 1.1). International Energy Agency (IEA) projections of world energy consumption up to 2030 show that the energy mix should remain dominated by fossil fuels, with renewables expected to contribute 18% which is well below the 32% share needed for the world to be on track with the Net Zero Emissions by 2050 Scenario (NZE).[4]

According to current estimates, the world's stocks of conventional fossil resources amount to about 1 trillion tonnes of oil equivalent, which will cover only a mere 100 years at the current consumption rate. Solar energy seems to have a sunny outlook because it receives energy estimated at nearly 100 trillion tonnes of oil equivalent, nearly 10,000 times the global energy consumption. But it only works on paper. In fact, these numbers correspond to the sunlight that hits the whole surface of the globe, whereas other sources are measured only by the energy that they can produce in a useful way. It is clear that only a very small fraction of the energy received from the Sun can be converted into usable energy, since any fertile land will remain dedicated to agriculture, and the oceans as well as the areas close to the poles are difficult to exploit. The poles are also from a solar and economic point of view, not particularly profitable.

American business guru Jeremy Rifkin argues that renewable energies coupled with communication technologies will bring us into the era of clean and easily distributed energy after the demise of fossil fuels. For this reason,

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[2] BP Statistical Review of World Energy 2021 (2022), https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf.

[3] The tonne of oil equivalent (toe) is a unit of energy defined by convention as the amount of energy released by burning one tonne of crude oil and is worth approximately 42 giga/billion joules.

[4] IEA [1].

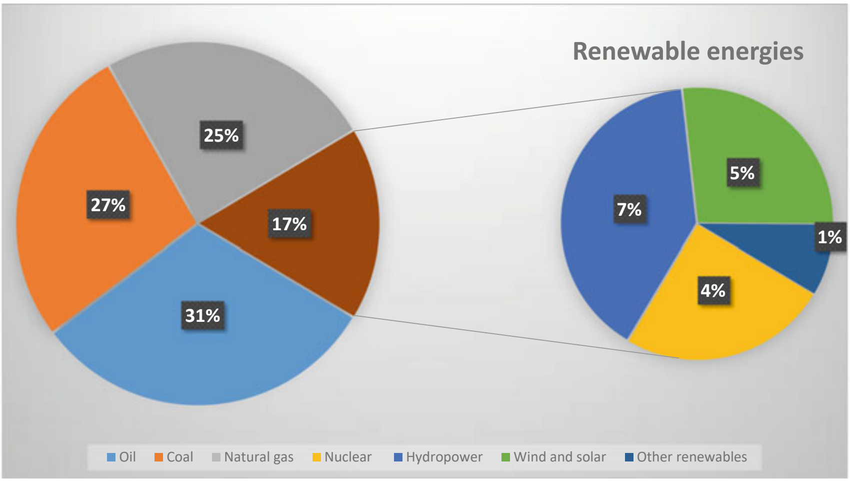

Fig. 1.1 Breakdown of the world's energy consumption in 2021. (*Source* BP statistical review of world energy, 2022)

he advises heavy investment in them.[5] Green technologies should, according to Rifkin, give rise to greater decentralisation of energy production and the emergence of a new sharing economy. This is a plausible scenario provided we implement the action plan that he recommends: massive investment in research and development; installation of micropower plants on all continents; industrial development of hydrogen technology; use of the internet to share energy as information; and replacement of the existing car fleet by rechargeable electric vehicles.

Several exploratory scientific studies carried out in various countries and political contexts seem to converge towards the idea that an energy supply based solely on renewable sources is possible by 2050, as supported for example by the work of the National Renewable Energy Laboratory (NREL), which aims at a "100% green" scenario for the United States[6]. However, let us keep in mind that the forecasts of these studies and the models used can change radically as the global economic and geopolitical context evolves. Who predicted the collapse of oil prices after 2012? Who predicted the war in Ukraine in 2022?

[5] Rifkin J [2].

[6] See also the work carried out in Europe, in particular by ADEME and the négaWatt association, who argue for the feasibility of a total conversion into renewable energies by 2050 as, on top of its advantages, it would lead to savings of hundreds of billions of euros and the creation of some 500,000 jobs in France: https://www.negawatt.org/.

At the end of 2016, under the title "Clean energy for all Europeans,"[7] the European Commission submitted to the European Parliament and the Council of Ministers a "package" of proposals to reduce the European Union's CO_2 emissions by at least 40% compared to 1990 level before 2030. The package had a second objective to modernise the economies of the European Union's Member States, creating jobs and supporting growth. Although Members of the European Parliament considered the package not ambitious enough in its remit, many support the idea of encouraging citizens to play an active role in electricity generation by supplying a large part of Europe's solar and wind electricity themselves. According to a recent study[8], "energy citizens" could produce up to 19% of the total electricity demand in Europe by 2030, and 45% by 2050.

It is true that solar energy and renewable energies, in general, are on the rise these days. In 2015, the 10th annual report of the United Nations Environment Programme[9] indicated that for the first time, more than half of the energy that could be generated by new sources connected to worldwide networks was from renewable sources (excluding large dams). We now invest twice as much in renewable energies than in fossil fuels (USD130 billion a year), and prospects for solar development, in particular, are very promising.

Europe is therefore active on the renewable energy front. In fact, the agreement reached at the end of the Conference of the Parties (COP-21)[10] held in Paris from December 5 to 12, 2015, broadly reflected the approach promoted by the European Commission on behalf of the 28 EU Member States. Following the success of the conference and the approval of the Paris Agreement by 195 delegations (plus the European Union)[11], a result rightly described as "historic," Europe has made climate protection one of its main priorities with the aim of achieving an "Energy Union." Of course, there is still a lot of work to do. And inevitably, one wonders whether these big events are useful as there seems to be a big difference between the messages in the speeches and the real intentions of the so-called decision-makers. The reality of politics or just hypocrisy? Superficial decision or genuine indecision?

[7] European Commission [3].

[8] Kampman et al. [4].

[9] McCrone [5].

[10] The Conferences of the Parties (COP) is the supreme decision-making body of the United Nations Framework Convention on Climate Change (UNFCCC). All states that are parties to the Convention are represented at the COP, which annually reviews its implementation and produces protocols and any other legal instruments to define obligations and commitments of the parties.

[11] To date (March 2023), 194 States and the European Union have ratified the Paris Agreement, of 197 Parties to the Convention, accounting for around 98% of global emissions, https://unfccc.int/process/the-paris-agreement/status-of-ratification.

Did the policy-makers address the problems in an efficient and comprehensive way? It is for you to judge. While a major cause of global warming is the pursuit of growth, there were not many people in Paris ready to slow down or even put upper boundaries to the process. "This loss of meaning," explained the yet to become French Minister of Ecological and Solidary Transition Nicolas Hulot in a book published a few days before the opening of COP-21, "is well-reflected by the structural failure of our current democracies to stop and prevent global warming.[12]" The global political decisions, although pointing in the right direction, take too much time to be implemented and do not respond quickly and globally enough to address the climate warming urgency. At the COP-27, which took place in the Egyptian resort town of Sharm El Sheikh on November 6–18, 2022, countries reached a historic decision to establish and operationalise a loss and damage fund, particularly for nations most vulnerable to the climate crisis. Although most welcome, the response did not seem to fully apprehend the many weather abnormalities which happened across the world in 2022 (heat waves, floods, extreme weather events, etc.) as the planet Earth experienced its sixth warmest year to date since global records began in 1880.

However, solutions do exist, and it is probably wise to investigate several options in parallel. Like investing heavily in "green technologies," the option favoured by the Bill Gates' Breakthrough Energy Catalyst, a private–public fund backed by the billionaire, which announced in January 2022 a "programme [to] finance, produce and buy the new solutions that will underpin a low-carbon economy"—the aim of which is to help invest up to USD15 billion into clean technology projects across the United States, the UK and the European Union. One can argue that it is a solution that can only be afforded by a wealthy country which also benefits from a powerful system of scientific research and technological development. In terms of more down-to-earth options, a recent report[13] urged the world to cut carbon pollution as much and as fast as possible and to embark in an unprecedented effort to transition away from fossil fuels and to remove carbon dioxide from the atmosphere on an ambitious scale. Another option is to radically change our way of life. Or, put the responsibility for controlling global warming in the hands of an international body that can make a truly coordinated worldwide effort. Against this background, two factors must temper our expectations regarding

[12] Hulot [6].

[13] The reports from the Intergovernmental Panel on Climate Change show that it is still technically feasible to avoid a 1.5 °C rise in temperature. For this purpose, emissions will need to reach net zero around mid-century. A USD13.5 trillion is estimated to be necessary to make the energy transition. The reports also show that 2 °C is a critical threshold for the planet. See in particular IPCC (2018) Global warming of 1.5 °C. Switzerland, IPCC, http://www.ipcc.ch/report/sr15/.