Michel Claessens

ITER: The Giant Fusion Reactor

Bringing a Sun to Earth

Springer

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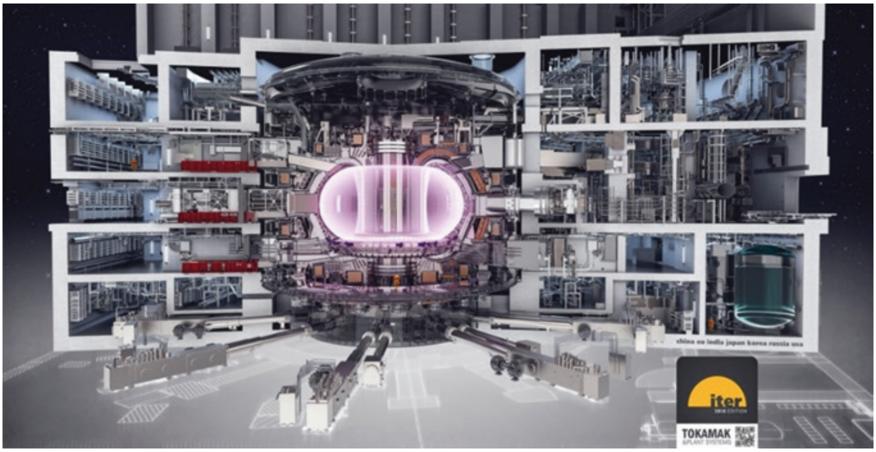
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Foreword by Daniel Clery

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, 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 3 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

Daniel Clery
Journalist with Science Magazine

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 (particular through a number of information exchanges and interviews) in the last several months or before. A special mention should be made of Jean-Marc Ané, Carlos Alejaldre, Robert Arnoux, François d'Aubert, Robert Aymar, Bernard Bigot, Philippe Busquin, Ken Blackler, David Campbell, Yvan Capouet, Daniel Clery, Laban Coblentz, 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, 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, as well as many more whose names I have forgotten. I hold their contributions in high esteem, even if they are anonymous and invisible—except to me.

I am also grateful to the people who have greatly improved the quality of this book by pointing out an impressive number of errors, inaccuracies, and omissions. I want to particularly thank Alice Whittaker and Giulia Marzetti, 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. Last but not least, I am very grateful to my wife Xuling for tolerating the several months when my brain could think of nothing other than ITER and highly energetic plasmas…

Popularizing 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 Anthony Doyle, in particular, for publishing a book on ITER. A final remark: the opinions expressed in this book are my own and do not in any way represent those of the European Commission or the ITER Organization where I used to work as a science communicator.

Readers wishing to be kept informed about the evolution of ITER are welcome to follow me on Twitter @M_Claessens or email me at michel_claessens@yahoo.fr.

Bruxelles, Belgium Michel Claessens

Introduction

On November 17, 2010 in Cadarache (close to Marseille), under 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, established almost four years before to coordinate an ambitious international nuclear fusion research program. It was indeed on November 21, 2006 that the biggest economic powers of the planet gathered in the Elysée Palace in Paris in the presence of 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 traveling to Cadarache for this highly symbolic ceremony the members of the Council were not shy about showing their happiness: after 22 difficult years of preparation, conceptual design, and detailed planning the project[3]

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

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

[3]A *project* is often described as a singular effort of defined duration, while a *program* is generally comprised of a collection of projects. The reality is a bit more complex, but in this book we consider a program tends to involve a bigger team and to have greater levels of uncertainty. ITER is actually both.

was finally born. As French journalist Robert Arnoux and physicist Jean Jacquinot put it in 2006: "In Cadarache, along the banks of the Durance River, a dream long considered to be a chimaera, will materialize. 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, 13 years later, the adventure continues: construction is progressing on the site and assembly of the machine has just begun.

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 hundred 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 an almost inexhaustible fuel (hydrogen) and produces little waste. ITER will therefore produce a "green nuclear" energy without any major drawbacks. The advantages are therefore high. The seven members of ITER, who committed to build the machine together, realized this quite a while ago. By mobilizing considerable resources and several thousand people around the world ITER is, in some respects, not so much different from World War II's Manhattan Project, albeit in the field of scientific research. It is possible that ITER will revolutionize nuclear power forever.

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 (the first experiments will take place in 2025 at the earliest) and the budget is quadruple its original size (according to the latest estimates the construction alone will cost more than EUR20 billion,

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

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 with the Apollo program due to its technological sophistication and its potential to irreversibly modify the course of history and the future of our civilization. The 7 ITER members actually represent 35 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 it 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 within 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 policy-makers that they hold the key to our energy future? What is ITER in the end? A revolutionary program likely to save our civilization, 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 that 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 evangelist 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 specialized and compartmentalized that such a book would have to involve dozens of coauthors 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 contextualize the program 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 program and summarizes what has been accomplished, without avoiding the drawbacks and issues that accompany the project. I'll also occasionally digress with some notes, personal memories, and anecdotes because, as the current Director General Bernard Bigot recalls, 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 endeavor that deeply pervades all of us. Transforming matter can also transform our mind and values. Some colleagues even feel they are 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 program 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 program and why? What are the risks? How is such a complex undertaking being managed? And finally the fundamental question, perhaps more important than all the others: Will the ITER star ever shine? Due to recurring delays and 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 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 under development for over 30 years the most skeptical state that it will always be

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

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 organized 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 program. 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 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.

ITER in Numbers[6]

23,000 tonnes. The ITER reactor ("tokamak") will weigh 23,000 tonnes, the weight of three Eiffel Towers. Approximately 1 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 kilometers. The 18 toroidal field coils (each 17 m high) will be wound from superconducting strands made from a niobium–tin alloy (Nb_3Sn). Some 100,000 km of these strands have been fabricated by industries in six of the seven ITER members—China, Europe, Japan, Korea, Russia, and the United States. This is record-beating production.

104 kilometers. The heaviest components of the ITER machine will be shipped to Fos-sur-Mer, the French harbor on the Mediterranean Sea closest to the site. Then they will be transported along 104 km of specially modified road known as the "ITER itinerary". The dimensions of these components are mind-blowing: the heaviest, the cryostat base, will weigh nearly 900 tonnes including the transport vehicle; the largest, a ring magnet manufactured in China, will be approximately four-story—or about 10 m—high.

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

4000 people. More than 3000 people work today at the headquarters of the international organization and on the ITER worksite. This number should exceed 4000 at the peak of construction and assembly activity (around 2021).

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 organizes two "Open Door" days a year.

Fig. 1 An aerial view of the ITER worksite in Cadarache (close to Marseille) in July 2018. The site has a total area of 181 ha. (*Top left*) The main warehouse that is used to store the reactor parts delivered by the seven ITER members. (*Foreground*) The personnel car park and the headquarters of the international organization (the building that skews to the right and whose façade is in the shade). The reactor will be located in the concrete cylinder next to the tallest building on the platform (known as the "assembly hall"). Nearly 3000 people are currently working at 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 about 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 the 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 criticized ITER. But high-level government officials have very different ideas . "We would be crazy not to achieve ITER", said Geneviève Fioraso,

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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 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 about 80% of the energy consumed. The pressing reality of climate change therefore calls for a radical and urgent change in our relationship with 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 policymakers to set clear goals regarding 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 rationalize 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. Most of the world's scientific community is convinced that scientific and technological mastery of this energy is within reach. To demonstrate this the seven members of ITER, grouped in the international ITER Organization, decided in 2006 to build an experimental fusion reactor in Saint-Paul-lez-Durance in the forest of Cadarache, which should achieve net energy production for the first time in history.

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

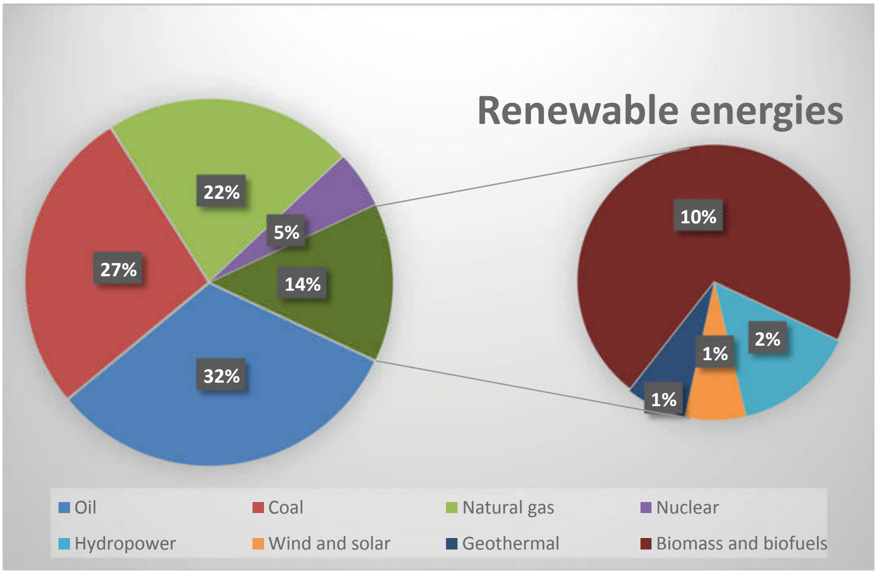

Fig. 1.1 Breakdown of the world's energy consumption in 2016. From International Energy Agency, World Energy Balances 2018

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 the International Energy Agency, world energy consumption, which is best measured by total primary energy supply, was in 2016 13,761 million tonnes of oil equivalent,[2] up 49% since 1995 (see breakdown in Fig. 1.1). IEA's projections of world energy consumption up to 2030 show that the energy mix should remain dominated by fossil fuels, with renewables contributing less than 10%.

According to current estimates, the world's stocks of conventional fossil resources amount to about 1 trillion tonnes of oil equivalent, which will last 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

[2]Tonnes of oil equivalent (toe) is a unit of energy defined by convention as the amount of energy released by burning 1 tonne of crude oil and is equivalent to approximately 42 giga/billion joules.

in 2016. 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 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 he advises heavy investment in them.[3] Green technologies should, according to Rifkin, give rise to greater decentralization 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 existing fuel-driven automobiles by rechargeable electric vehicles.

Several exploratory scientific studies carried out in various countries and political contexts seem to converge toward 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.[4] However, we should 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?

At the end of 2016, under the title "Clean Energy for All Europeans",[5] 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 with the 1990 level before 2030. The package had the second objective of modernizing 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

[3] Rifkin [1].

[4] See also the work carried out in Europe, in particular by ADEME and Association négaWatt, who argue for the feasibility of total conversion to renewable energies by 2050 since in addition to 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/.

[5] European Commission [2].