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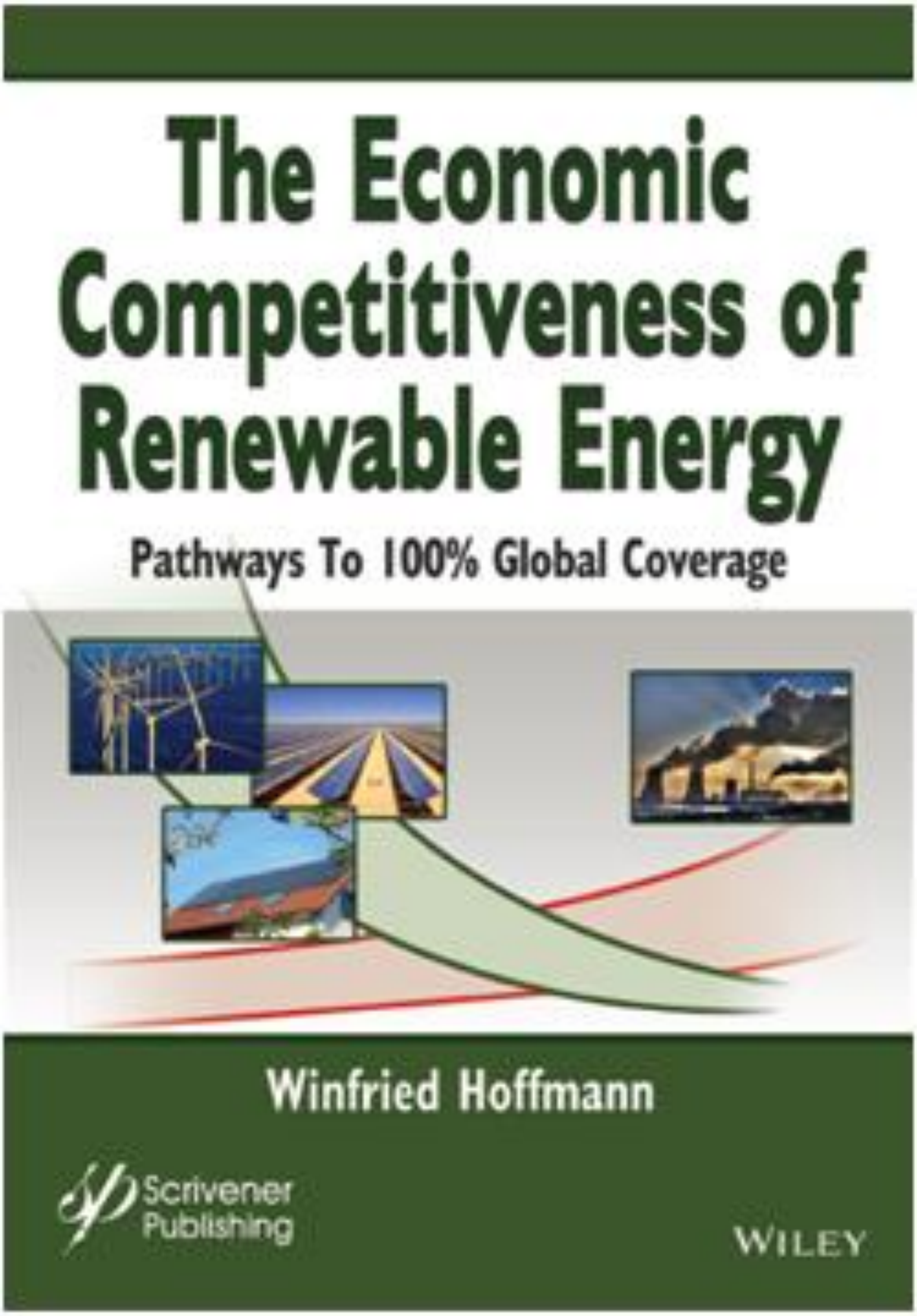

PREFACE

It is the pretension of this book to give a comprehensive picture of today's energy world, to describe the potential for energy savings which can be achieved and to get an understanding of technology development which will lead to a 100% renewably powered world as the most likely situation. This is based on the long-term economic and ecological superiority of renewables over traditional energy sources. It is the combination of these topics which makes the book unique. This abstract can also be used by the reader to make his or her own sequence for the 11 chapters according to personal preference – although for those who are no experts in the field it is useful to follow the given order.

The **INTRODUCTION (Chapter 1)** starts with a description of a general phenomenon, namely the fundamental changes taking place in the world we are living in today, not only in the area of energy but also the way in which we communicate and exchange information across the globe. It critically analyzes what the general public is told by incumbent political and industrial institutions. It is this change which lays the ground for a major alteration including in how to use and produce our daily energy - from centralized systems back to municipal and even individual levels. Environmental concerns and the growing awareness about the finiteness of traditional and affordable primary energy (fossil and nuclear) will accelerate this change.

The **ANALYSIS OF TODAY'S ENERGY SITUATION (Chapter 2)** first describes basic energy terms for those who are not experts in this field. Today's global energy situation is analyzed in form of primary (140 PWh), secondary (90 PWh) and end user energy. The various energy sectors – mobility, industry and private/office/SMEs (small and medium enterprises) – where the secondary energy is used, are specified.

When analyzing the potential of the various exhaustible energy sources and simply comparing the total sum to our current energy usage per year, it is tempting to simply divide these two numbers. The result varies – depending on how many unconventional sources are considered – between many centuries and up to two millennia. It is emphasized that a much more differentiated look must be taken.

There are major challenges for fossil energy: finiteness leading to "peak oil and gas" in the foreseeable future will result in increasing prices and CO_2-emissions, which either will add significantly to the generation cost (if carbon capture and storage can be realized) or will cause irresponsible temperature increases due to Greenhouse Gas emissions. A journey through the history of our earth dramatically outlines what we are currently doing by passing the CO_2-concentration of 400 ppm due to burning fossil fuels. Such a level was only seen millions of years ago. Accelerating factors of global warming like the melting of glaciers and permafrost thawing are also described and add to the imperative: we must ACT NOW!

The problems with nuclear technology for all reactor types, fission, fast-breeder and fusion are detailed and it is shown that these problems simply add to the inferiority of this type of electricity production; an inferiority which already stems from their higher generation cost compared to renewables – assuming no subsidies for either technology.

The **IMPORTANCE OF EFFICIENCY MEASURES (Chapter 3)** has nothing to do with renewable technologies but the measures described will help a lot to achieve a 100% renewable contribution sooner rather than later. The importance for the general public to understand that efficiency measures will not decrease their comfort of living but will give them the "same quality of life with much less energy" is highlighted. In conjunction with renewables as secondary energy provider this will even change to a "better quality of life with much less energy".

Emphasis is placed on the fact that many energy efficient products have a higher price when purchased compared to older ones which, however, is more than offset, when the total life cycle cost or levelized cost of service is considered as shown through the example of future lighting. The superiority of electro mobility will only evolve if electricity is provided by renewable technologies. The significant savings in heating and cooling energy for houses will be seen with well insulated houses in the future, which will in parallel lead to less solar thermal appliances. As a summary, the secondary energy which would be required today with the available energy efficiency measures (~45 PWh) within the various sectors is given. A recommendation to politicians is provided on how best to accelerate the introduction of energy efficient products, namely through reasonable support for the new technologies and not simply by banning the old ones.

An **OVERVIEW OF THE MOST IMPORTANT RENEWABLE ENERGY TECHNOLOGIES (Chapter 4)** starts with an outline of the huge potential of renewable energy resources. The outstanding offering from solar irradiation exploited by three technologies – decentralized PV, centralized concentrated PV and solar thermal as well as solar thermal low temperature – is highlighted. Simply considering land use and near-shore coastal regions for wind off-shore ("technical potential"), we can provide 880 times today's secondary energy through renewable energy and when simply taking today's technologies and feasible areas ("sustainable potential"), ~35 times today's secondary energy could be provided (and 21 times the future secondary energy needs for our 100% renewably powered world).

The historical developments of technology and market are detailed for wind energy as well as for solar thermal collectors and concentrators. Readers will understand why wind turbines are getting higher and higher to make best use of the wind conditions at a given site. An overview of PV and other renewables (hydro, geothermal, wave and tidal) is also given.

The **PV MARKET DEVELOPMENT (Chapter 5)** starts with a topic which is addressed to economists, in particular to liberal ones. When it comes to the question of whether support schemes are useful or whether only free market mechanisms should decide on certain technology developments it is advisable to differentiate between strategic goods – such as electricity production, transportation – and consumer goods – like mobile phones or televisions. It is shown that while for the second group the free market mechanism is the right instrument, this is fundamentally different for the strategic goods. When it comes to the question of whether support for a technology should be organized through market pull or technology push, the clear answer from an industrial point of view is through market pull.

The development of a multitude of different customer needs for PV products and the associated market volume is discussed from the 1970s until today. The unimaginable average market growth of more than 50% per year in the first decade was only possible due to the support scheme in form of the Feed-in tariff, where renewable technologies went along with a long-term payment (typically 20 years) for all produced electricity based on the respective cost plus a positive margin. Based on the ideas by Wolf von Fabeck and municipal experience in Switzerland, it was Hans-Josef Fell and a good number of supporters who first got it politically up and running in Germany, after which it spread out into more than 60 countries worldwide. The total budget for these payments (minus the stock exchange value) can be seen as an investment by society and it is shown that the associated Net Present Value is clearly positive with conservative assumptions. Even if there is considerable outcry over the many billions spent on this investment, it obviously pays off when analyzed over the long-term payment period. The fact is that after this time period our children will benefit from a "golden age" in which electricity is produced at marginal cost with depreciated PV systems throughout their life-time which is significantly longer compared to the typically 20 year's payment time period.

In times of high annual growth as mentioned above, some bottle-necks along the value chain (e.g. poly silicon) appeared, resulting in an increase in prices. This was taken as a signal to invest in additional production capacities all along the value chain. With clear industry political goals coupled with a number of clever entrepreneurs it was Asia, particularly China which increased its global share in PV module production from about 5% in 2005 to 60% in 2012. Unfortunately the capacity increase outgrew the market volume which resulted in about 100% overcapacity in 2012. As in every industry the consequence is now a shake-out of production companies associated with (too) low product prices and deep red numbers on the balance sheet. The flipside of this situation is that it allows new markets to establish themselves which would not have been realistically possible only a few years ago. After this consolidation period and a further market growth we will see a new wave of production facilities which, with new ideas from the R&D-institutes, will enable cost numbers which are low enough to achieve positive margins at today’s prices. In 2013 we are in a time where we clearly foresee the end of the running Feed-in tariff program in only a few years, which leads to the necessity to install a new market design for the future increased levels of renewable electricity including the procedure how renewable electricity is traded on the stock exchange. The development of electricity storage, Demand Side Management, smart grids and virtual power stations is described.

The **PV VALUE CHAIN AND TECHNOLOGY (Chapter 6)** summarizes the various PV technologies c-Si wafer and Thin-Film in greater detail, but also describes concentrated PV, Dye solar cells and organic devices. Besides modules, the additional components for a complete PV system such as inverters and BOS (Balance Of Systems) components are also dealt with. Based on a number of examples an important observation is described: the power of continuous development and economy of scale versus breakthrough technologies to decrease production cost is most often underestimated.

THE ASTONISHING PREDICTIVE POWER OF PRICE EXPERIENCE CURVES (Chapter 7) shows impressively what even research and industry people from the same technology sector could often not believe. Such curves plot the cumulated volume of a particular product versus the respective price in a double logarithmic scale. From the slope one determines the %-change in price for each doubling of cumulative volume. With the example of DRAM semiconductor devices it is demonstrated that all people strongly believed in the 1970s/1980s that the slope was horizontal – i.e. no further price decrease – after the 1990s. Yet 20 years later we are still running down this same graph. Similarly for Flat Panel Displays such a development has been on-going since the 1990s.

Emphasis is placed on the fact that while big and centralized technologies have more of a project character for specific regions, small and mass produced components which are globally produced and internationally traded have a high probability of producing significant cost and price reductions. Examples of centralized technologies are power stations; examples of mass produced components are PV solar modules, batteries and fuel cells.

The Price Experience Curve for solar modules (c-Si and Thin-Film) is shown as well as for inverters and by analogy to the examples given before, there is sound reason to believe in a further continuation of falling prices. Deviations from the slope can be explained by e.g. product shortage for prices above and overcapacity for prices below the Price Experience Curve.

The **FUTURE TECHNOLOGY DEVELOPMENT (Chapter 8)** is discussed for all renewable technologies. The potential price development is based on the respective Price Experience Curve

For **FUTURE ENERGY PROJECTIONS – THE 150 PW-HOUR CHALLENGE (Chapter 9)**, some well-known projections from the IEA and Greenpeace are shown for reference. The market development for the various renewables and their potential market share are described in some detail. Reasoning for a simple split to cover the required 150 PWh of energy for future secondary energy is explained: decentralized PV, centralized concentrated PV and solar thermal systems, decentralized low temperature heat, wind energy and the rest of all other renewables provide 20% each, or 30 PWh of energy.

Realizing that if renewables will take over the 100% energy supply there will be huge industries for all technologies and therefore a great opportunity for all economic regions to grow a sizable industry for this future. Individual companies should be encouraged to make an extra effort to be in that business. With the example of PV it is estimated that the annual overall turnover in the 2040s will be comparable to the global annual turnover for the automobile industry.

The **LIKELIHOOD AND TIMELINE FOR A WORLD POWERED BY 100% RENEWABLES (Chapter 10)** deals with the potential development. While some years ago the need for a global network in form of a worldwide super grid was seen as an elegant solution, a new model may emerge: local autonomy for the decentralized private and SME sector and relocation of the energy intensive industries, which need power and process heat, close to places which cost effectively deliver energy from the centralized hydro, (concentrated) PV and (off-shore) wind parks (sometimes it may be more cost effective to link power intensive industries via transmission lines to the big renewable power stations).

In **CONCLUSION: THE 100% RENEWABLE ENERGY PUZZLE (Chapter 11)** summarizes the findings and discussions from this book in form of a 3 by 3 element puzzle. The limit of a 2°C temperature increase can only be accomplished if we shift all fossil power stations to renewables as quickly as possible. Nuclear is not a viable alternative for safety and cost reasons. Driven by mass produced products like solar modules, batteries and other devices which are important for the future 100% renewable world the cost and price decrease will demonstrate the economic superiority of renewables over traditional fossil and nuclear technologies by the 2020s at the latest. Once this is recognized by the financial community there will be a substantial re-allocation of huge investment money, away from traditional technologies and a steady move towards the 100% renewably powered world.

CHAPTER 11: CONCLUSION: THE 100% RENEWABLE ENERGY PUZZLE

The most important arguments for a future 100% renewably powered world are summarized in Figure 11-1. There are basic objections to a Business As Usual scenario as summarized in the reddish elements of the puzzle:

- Nuclear is a "no go" because of safety considerations which is not 100% guaranteed, and because of the unsolved waste storage problem. Nuclear also has no economic future: based on recent discussions between EDF (France) and British ministries the cost of new built nuclear power is such that an agreement was made tp pay €ct11.2/kWh for 35 years for each produced kWh plus adjust for inflation. In addition, uranium resources for fission reactors are rather limited and could only be stretched if reprocessing is considered, which would cause additional safety and proliferation problems. Furthermore the use of 3rd and 4th generation reactors like fast breeders would only add significantly to the safety problems. Fusion reactors are not being considered because if technological challenges were to be solved at all I am convinced that firstly they would not be feasible for the preferred decentralized energy production technologies and secondly they would be more expensive than renewables.

- Fossil energies pose either an environmental problem when CO_2 is released and contributes to global warming at unacceptable levels, or a cost problem if CCS is considered which adds significantly to the LCOE –if the long term storage can be solved at all. The topic of climate change is summarized well by Rahmstorf and Schellnhuber [2-12]. Traditional exhaustible energy sources have the natural disadvantage that despite new findings today they are definitely limited tomorrow and will bring with them increasing costs for unconventional future sources (e.g. deep water oil and gas reserves in the arctic sea). Once the time of peak gas and oil will have passed, markets will react with increasing prices.

Reasonable & industrially proven growth rates for all relevant RE	**Quick change to RE (early invest) costs much less than BAU (repair the damage)**	**Price Experience Curves for PV, wind, storage like semi & FPD →low LCOE**
Portfolio of RE including storage solutions solves variability	**100% renewable Energy for All Global Secondary Energy Needs in 2050+**	**Energy Efficiency: with RE even better quality of life with much less energy**
Turnover for the PV sector alone comparable to automobile turnover	**Fossil energies problems with CCS: not working or more expensive**	**Nuclear is no go due to cost, safety and unsolved waste storage issues**

Figure 0-1: The 100% renewable Energy (RE) puzzle

Fortunately there is good evidence that a future energy supply can be provided environmentally safe, economically superior and with security of supply regionally, globally and forever. The major arguments for this are summarized in the greenish elements:

- Although not directly coupled with RE, energy efficiency measures for all appliances and products are important for a future world. This will help to have the same – with renewables even better – quality of life with less secondary energy – with renewables even eliminating the problem of energy losses through conversion from exhaustible primary to secondary energy. The ideas by Weizsäcker et al. "Factor 4: doubling prosperity – bisected consumption of nature" and "Factor 5: the formula for sustainable growth" summarize this topic nicely.

- The portfolio of all renewables – most importantly solar and wind due to their big technical, economic and sustainable potential – will already smoothen the energy delivery compared to the load curve required by consumers. The challenge of variability of the various renewables will be solved through the storage of electricity directly in batteries and pumped hydro as well as indirectly with power gas from surpluses in renewable power. Most likely a dramatic change will take place with regard to distributed and centralized renewable energy production and its respective usage. The decentralized electricity production through PV and local on-shore wind mills as well as heat by solar thermal systems will develop a situation of greater autonomy for private households, SMEs and offices in local areas. This will take place with the support of small and medium sized storage systems and the integration of the range extender from electric cars for power balancing. The large and energy intensive industry (metal smelters, chemistry etc.) will either concentrate close to the centralized power stations by hydro dams, off-shore wind farms and very large PV parks or, when economically more attractive, high voltage DC grids can transport electricity to the respective industry.

- Besides the fact that renewable primary energy sources (solar, wind, hydro, bioenergy et al.) are abundantly available, the decrease of the LCOE for the various energy converters like solar modules, wind mills etc. is widely underestimated. This can be predicted on the basis of the Price Experience Curves for the various energy converters that contribute to the continuous further cost decrease similar to the well-known examples of semiconductor devices, flat panel display products and many more. Similar considerations hold true for battery systems and fuel cell devices. Table 11-1 summarizes the previously discussed LCOE's for PV and wind and estimates electricity storage for the time 2030+. The LCOE for clean coal and nuclear fission is also given for comparison. It is interesting to compare the sum of wind or PV plus storage with the traditional LCOE, which is roughly the same with one important difference: while there is no proven fact today whether CSS will really work and if so at what additional cost, the renewable technologies are based on solid projection from technology development of the past with PECs looking towards the future.

Category	Technology	LCOE in today's currency [$ct/kWh]
Traditional	Clean coal with CSS	~10
	Nuclear fission	>~10
Photovoltaics	Southern areas (~2 kWh/W_{PV})	3 – 4
	Northern areas (~1 kWh/W_{PV})	6 – 8

Wind	On-shore (~2 kWh/W_{wind})	3 – 4
	Off-shore (~4 kWh/W_{wind})	4 – 5
Storage	Small (~kWh+)	6 – 8
	Large (~MWh)	<5

Table 0-1: Estimated LCOE's in 2030+ for various technologies

- Although it is by no means scientific proof but rather a well observed phenomenon, the Kondratieff cycles are continuing, in particular the current 6th one which is mostly associated with "Man's Health" in a broader and more general sense. For example the introduction of RE is one of the important features for this current cycle which should come to an end around 2050 by analogy to the first 5 cycles. This would imply that by then the economic large scale introduction will have happened and the beginning 7th cycle will concentrate on new challenges. If we calculate average growth numbers for the various renewable Energies from today to the PWh necessary to provide 100% energy supply by 2050 (150 PWh) we can see from Table 11-2 that no unrealistic growth has to be anticipated – just remember the average growth for PV in the first decade of this century, which was well above 50% per year.

	~2010+/-		~2050+			
	GW	TWh	TWh	TWh	GW	CAGR [%] p.a.
Photovoltaics	~100	~120		~30,000	~23,000	+ 14.8
CPV/CSP	~ 1	~ 2		~30,000	~17,000	+ 27.2
Solar thermal	~190	~130		~30,000	~44,000	+ 14.5
Wind	~280	~600		~30,000	~10,000	+ 10.3
Bioenergy	-	~14,000	↓ ~10,000			substitute
Hydro	~850	~3,500	↑ ~8,000	~30,000	-	+ 2.1
Geothermal, wave&tidal, etc	-	~ 5	↑ ~12,000			+ 21.5
Total	1,421	18,357		150,000		+ 5.4

Table 0-2: Anticipated CAGR (Compound Average Growth Rate) for renewable Energies from today to 2050 (own estimates)

- Even if some RE technologies today show a slightly higher LCOE compared to traditional technologies, one must not forget that traditional energy production will become more expensive while RE will decrease their LCOE continuously (see Table 11-1). Additionally it is not highlighted that e.g. fossil energy receive more support money compared to the whole RE sector: the IEA WEO 2010 report states that in 2009 312 billion $ were spent globally for consumption subsidies to fossil fuel while only 57 billion $ were given as support to ALL renewables. It is also mentioned that the internalization of external cost has been ignored. Alternatively, as described by N. Stern, each dollar of what is not invested in RE today has to be paid at a substantially higher level at a later date due to the damage caused by on-going traditional energy technologies (storms, droughts, sea level rise and many more).

- After all the renewable pathway opens also a new large scale industry in all areas. Just for the PV sector alone it was estimated that with the growth rates and price developments assumed the turnover becomes in the 2040s comparable to today's global turnover in the automobile industry, which is a $1.5 trillion industry.

- As a consequence of all surrounding elements we arrive 'almost automatically' at the central element in the dark green middle of the matrix, which calls for 100% renewable Energies for the global secondary energy needs in the future. The interesting question remains as to when this will have happened. Knowing that in Germany a number of municipalities have started to set a precise date around the 2020s to have a 100% RE supply, one could envisage that Germany could indeed demonstrate the same as a whole in the 2030s. It very much depends firstly on what those municipalities are able to achieve in terms of cost and secondly on how the still existing old and not optimized building stock can be changed efficiently. Should, however, an economy like Germany indeed be able to demonstrate that a change to 100% RE is not only positive for the environment and human health but that it is also in the foreseeable future – which can be easily calculated – superior to the incumbent traditional energy system, it would certainly trigger an international imitation. During which decade the 100% RE world will have happened will be subject to joint discussion – for all of us who are still around –in the decades after 2050.