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Review

Economic Issues in Deep Low-Carbon Energy Systems

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Abstract: The main interlinked challenges to achieve a low-carbon emission economy are analyzed. It is argued first that there are no obstacles to a free market working effectively with a high penetration of distributed Renewable Energies (RE), since intermittency has been overstated, and affordable storage solutions are available because of strong learning rates. Demand-side management policies are promising too, neither are there foreseeable boundaries to the availability of economically extractable photovoltaic and wind energies. A full 100% RE system may be more challenging though, partly because bioenergy, a key dispatchable source in most available RE roadmaps, clashes with growing food needs and reforestation to counter greenhouse gases emissions. Similarly, the green growth proposal is constrained by materials availability, mainly cobalt and phosphorus, which will also constrain the deployment of electric vehicles. Alternatively, the United Nations Human Development Index may be a more suitable target for a sustainable RE system. Although history is not reassuring, the main global economic hurdle is possibly existing fossil fuel-related investments, likely to become stranded. An assessment of their value yields a substantially lower figure than is sometimes claimed, though. Finally, a limited role for nuclear energy is assessed positively, provided it is publicly owned.

Keywords: merit order and competitive markets; renewable energy boundaries; critical raw materials; transportation; land; speed of transition

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1. Introduction

As the climate change issue has become increasingly pressing [1], several pathways and scenarios put forward by academia and policy think tanks alike for a transition to a deep low-carbon economy are continually growing. The IPCC, in its latest review [1], has assessed mainly integrated assessment models (IAM) that rely on the optimization of general equilibrium economic models, usually assumed to be market-based and competitive. The main drivers for emissions reductions in these models are carbon taxes exogenously determined by policymakers at a suitable level, enough to deliver the desired emissions reduction targeted. These models struggle to account for hallmark disruptive changes, notably from innovation and costs reductions endogenously derived from learning rate (LR) effects, and other nonlinear changes induce by human behavior, like consumer choices. The approach followed by the International Energy Agency (IEA), in its published research, shares several similarities to these IAM models, and given its relevance, since it is an OECD government-supported think tank, it will be discussed here [2,3]. The International Renewable Energy Agency (IRENA) is likely the second most prominent and government-supported international think tank that regularly produces reports detailing transition pathways. Specifically, the most recent [4,5] will be assessed. The roadmaps (RM) laid out by these two agencies aim for a high degree of renewable energy (RE) to meet future demand, typically above 90%, and are derived as a backcasting exercise from detailed projections and targets for the year 2050. While the IEA's approach is based on cost minimization for the total system energy output discounted at current values, IRENA's are derived from a backcasting exercise, loosely related to the optimization of individual energies deployment and constrained by estimated feasible paths.

Other research, mainly produced by academics, has looked at the feasibility of 100% RE solutions, well-known examples being [6,7] derived from a backcasting exercise resembling IRENA's, and [8] derived from a system cost minimization for the overall energy generated.

Low-carbon RMs and 100% RE solutions are being published almost relentlessly, underlining the struggle to thwart climate change, but also because of the relative ease generating them, once the data have been collected and with available public software [9]. At the local level, be it continental, national, or even town level [9], there are many RMs available as well, their usefulness being somewhat limited by geographical scope, though. They are generally derived under the main principles considered for world RMs, i.e., optimization of some adequately cost criterion, or as backcasting exercises. Summarizing, the RMs considered here are a fairly representative sample of the work being conducted in this field. These low-carbon pathways proposals, and renewable energies solutions in general, have been criticized, heavily in the case of 100% RE solutions, a recent example being [10] that, in turn, has prompted quick answers by [11,12].

Criticisms focused in the past on the twin issues of intermittency and storage and the costs involved. Defendants have always argued that the LR of these technologies would eventually bring down costs to competitive market levels, although critics have dismissed the LRs statistical estimates. However, experience and careful analysis have again disproved these criticisms [13,14]. Even recently, photovoltaic (PV) energy has been shown to be cheaper than running coal factories in large parts of the US [15], and PV and other REs are expected to become market competitive all over the world by 2030 in the less optimistic assumption. In response, critics have switched the criticisms to other more potentially damaging aspects. First, taking the merit order hypothesis to the extreme, they argue that fossil energies are necessary, even if REs are cheaper [16,17], and that capacity markets and other forms of subsidies for fossil energies will be required in the event of REs becoming cheaper; e.g., [18–21]. Second, a variety of neo-Malthusian strands of the literature argue that: (a) planet earth is limited [22] and, therefore, growth, and particularly Gross Domestic Product (GDP) growth, be it based on fossil or Res, cannot go on forever; (b) that there are intrinsic limits to wind energy [23], biofuel [24], and even to solar energy, since there would be not enough available land required to supply a 100% RES, [25,26]; and finally, (c) that the raw materials needed to build turbines and PV modules, mainly the so-called rare-earths, are not sufficiently available [27,28].

Finally, there are several related questions that pose significant hurdles to such a deep low-carbon transformation: first, the overhauling of the transportation system, although already in [29], detailed proposals were made which have been systematically implemented in a model by [30]; second, the required speed of transition presents economic difficulties, but also political and social, and according to some authors, again, it is not feasible [31]; third, the availability of land, including arid land, for biomass and other RE forms of supply is under jeopardy, given the multiple uses that land has to cater for, e.g., food and dwellings.

The low-carbon transition is likely the most critical issue facing the world nowadays [1], and a growing body of literature is developing, dealing mostly with specific aspects independently. A global overview on the main interrelated issues may clarify their links and help identify critical points that deserve research, actionable by policy makers. The present research intends to be a step in that direction.

Plan and Objectives of the Paper

The main points raised by critics of the deep low-carbon REs proposals are gathered in Section 2 under six headings: Section 2.1 looks at the working of free markets from a purely economic perspective; Section 2.2 tackles the boundedness of planet earth from a general viewpoint; Sections 2.3 and 2.4 present criticisms pointing at specific limitations of RE supply and necessary raw materials; Section 2.5 considers intermittency and storage and finally, Section 2.6, an assorted set of related issues. Section 3 tackles these points in the corresponding subsections. A general discussion is presented in Section 4, along with some specific issues relevant in this context: the role of nuclear energy, the so-called stranded assets (SA) issue, and the adequacy of the optimization methodology for RM design. The conclusions in Section 5 provide a global assessment, and two appendices discuss analytical models of resource depletion and population projections.

2. Challenges for the Transition

The main interlinked challenges facing a transition to a low-carbon economy are identified and the framework for their discussion is laid out in the following sections. Then, Section 3 is devoted to a fuller discussion and assessment of the solutions. The topics have been identified through analysis of the current literature on the subject, and also with the usual follow-up of the cited literature and Scopus searches. Most can be classified broadly into three categories: economic—working of competitive markets, intermittency, and storage; availability of resources—critical raw materials, land, wind, and bio energy; political—transition speed, stranded assets, etc.

2.1. Free Markets Cannot Work with 100% RES

The critics of the deep low-carbon and 100% RE systems (RES) argue that since REs run on free fuel, they incur no operating costs. Then, the cost of supplying one additional unit of energy at every possible supply level is zero, driving the energy market price to zero thereby when the atmospheric conditions are favorable, i.e., lots of wind and sun [16,18,32,33]. This is the so-called merit order effect. Then, fossil fuel energy producers with no negligible marginal costs are out-competed and run into losses, eventually being forced to leave the market [16,17]. A related criticism states that since REs are funded by subsidies, be they feed-in tariffs, quotas, or direct subsidies, they are prone to create overcapacity, increasing, therefore, the likelihood of oversupply and frequent zero market prices. This might end up undermining the very profitability of REs investments, i.e., what they call 'the RE policy paradox' [17]. What is even more, those subsidies would ultimately be paid by consumers through increased electricity market prices [16]. In addition, the inherent RE intermittency would require furthering capacity markets, which would also add to the bill paid finally by consumers [34]; finally, higher energy price could not be capped since that would lead to underinvestment and supply shortages [35].

Both lines of criticism are based on the assumption that REs are not dispatchable and can hardly be forecast, since they depend on intermittent weather, and because large scale storage solutions for energy at acceptable cost are not available. Then, and since energy demand is variable and cannot be easily managed, periods of unmet demand would ensue, e.g., a quiet windless night. The bottom line is that since only fossil energies are dispatchable, the market cannot run without them, and eventually, they will have to be protected. They put forward an array of solutions involving direct subsidies to fossil energy suppliers [36], capacity markets to ensure that fossil suppliers are available [19,20,37], taxing the private use of batteries to prevent self-consumption [21], and even stopping RE subsidies so that they compete at their actual levelized energy cost (LCOE) [16,18].

Other authors add the lack of land for PV and wind parks and necessary raw materials, suggesting a replacement of fossil by nuclear energy, or alternatively, a global downsizing of the world economy and population [38,39]. On a similar tack, the authors in [40] conclude that the whole financial system is at risk, since lower prices induced by RE will prevent banks from recovering their loans, thus, provoking cascade financial failures. Finally, the authors in [41] remark that under the second law of thermodynamics, energy degrades so that REs are not strictly renewable being, therefore, on an equal footing as traditional fossil energy sources.

2.2. Limits to (Green) Growth

The neo-Malthusians present a varied array of arguments to conclude that the current growth trends, particularly GDP and population growth, are unsustainable. An early and influential example was [22], based on the System Dynamics (SD) methodology, which amounts to a complex set of dynamic and interdependent differential equations intended to capture the stylized features of economic and related aspects of societal behavior. Their research was echoed in a much-divulged report to Carter's US presidency [42], that although less well-structured and formalized, led to similar qualitative results. This last report, in particular, helped kickstart the research in solar energy and PV above all. Another far-reaching implication was to raise awareness about the increasing needs of an ever-growing world population, leading to the implementation of population control and reductions programs in several less developed countries. Regarding this last point, and although even the United Nations (UN) expect world populations to stabilize around 10 to 11 billion by 2050 mainly as a result induced by increasing standards of living, the population model reported in Appendix B conveys a different message: it stresses, in particular, the risk of far more substantial increases with significant probabilities of doubling the UN projected values, reaching levels above 20 billion in some cases.

According to [43], an updated revision 30 years later of the original work in [22] showed its forecast accuracy. Their work boiled down to a world model yielding smooth growth for as long as 100 years or more, leading inevitably to sudden collapse as exponential resource consumption hits planetary boundaries. Despite the model complexity, the underlying assumption is simply that the efficiency of resource extraction investments decreases with time, leading to collapse because of ever-increasing demands.

A straightforward and otherwise realistic model can yield precisely those results, displayed in Figures 1–3—see Appendix A for model details. A constant (GDP) growth rate of 3% and energy and other material requirements equivalent to 7% of GDP are assumed. The Energy Return on Investment (EROI) is supposed to follow a linear decline pattern with values, $EROI_1 = 10$, $EROI_{100} = 1$ implying that at $t = 101$, the energy required to obtain one unit of gross energy is above one, so that the economy collapses, since net energy would be negative.

Figure 1 reflects the relatively slow decrease in the EROI that still, in 2090, decreases only 5%, and quickly drops down thereon. Figure 2 shows how a steadily increasing GDP requires accelerating energy supplies.

Figure 3 finally displays the resource time depletion behavior. The remarkable result is that the economy keeps growing smoothly for much of the century, and just keeping the same GDP growth rate leads to a sudden collapse in a few years without hardly any forewarning. The resource mined increases from 10% in 2095 to 70% in the final year, leading to exhaustion in just five years.

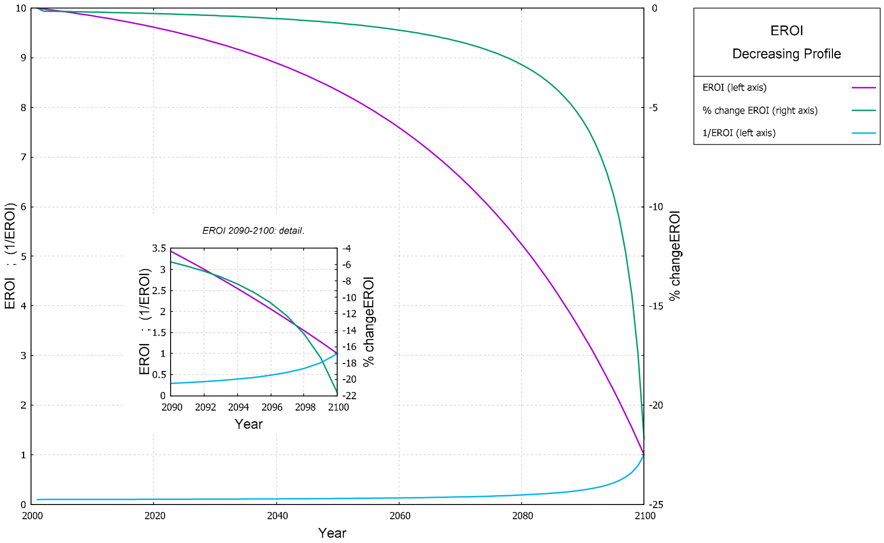

Figure 1. EROI Timeline.

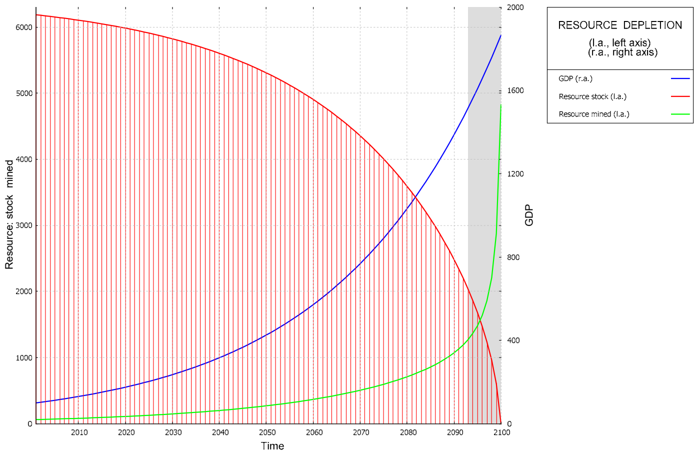

Figure 2. GDP and energy demand.

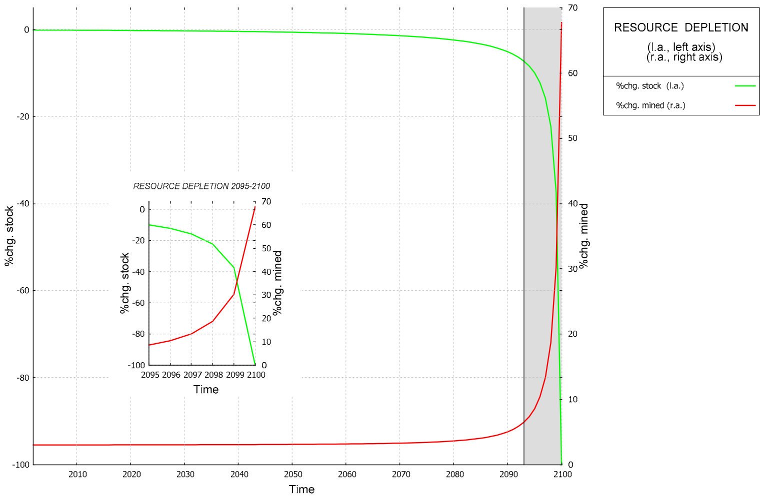

Figure 3. Resource depletion.

The authors of the report [22,43] suggested adapting to those limits constructively, switching to a kind of service economy more focused on ethic and spiritual values rather than on materials goods, i.e., research, health, education, arts, etc. Put simply, well-being should not be measured by material growth as given by GDP. After all, GDP is defined as the market value of goods and services produced by the economy, and although a useful measure at that, it cannot be taken as the overarching measure of well-being, since many aspects of human behavior are not marketed or cannot be priced. A particularly salient conclusion was that no level of technical improvement would allow overcoming the earth's physical limits, implying that material growth will stop entirely at some future date, whether in a planned orderly way or by uncontrolled collapse. This runs counter to the over-reliance on human ingenuity assumed in much of the current economic thinking. Recent proposals in the same vein are presented in [44], loosely supporting intellectual prosperity based on a service and leisure economy rather than on material goods production and consumption.

The EROI concept was developed in the early 1980s to analyze several issues related to fossil energies, and some authors point out that it does not apply to renewable sources and a fortiori to renewable energies [45]. For this assertion to stand, nevertheless, the energy required to produce the required capital, e.g., solar PV modules, onshore wind turbines, and biomass boilers, would have to come from renewable sources as well: in other words, only in a fully RE system that argumentation would strictly stand. Despite that, and while the conclusion of [45] may carry considerable weight—although some authors might question it [46]—the previous model and argumentation, laid down in (A7)–(A11) and Figures 1–3, can be applied more generally to any exhaustible resource, and therefore, the essence of the model holds its validity.

This methodology has also been implemented to model energy supply [46,47], both from fossil and renewable sources. The authors in [46] specifically, conclude that fossil energies, including nuclear, are close to their peak, and that renewables cannot make up for the slack since their availability is limited besides being too expensive, boiling down to high LCEs [48]. The bottom-line would be the unfeasibility of green growth, either because of the impossibility of supplying world energy from renewable sources or because of general physical earth boundaries.

2.3. Land and Other REs Requirements

Other authors claim that REs are by no means unbounded, contrary to common assumptions. The authors in [25,26] assess the limits to solar energy, concluding specifically that land requirements may not be enough for 100% RES solutions, at least for some countries. These results are obtained under a set of somewhat stringent assumptions, some of them not supported by the workings of current electricity systems already; see Section 3.3. Turning to biofuels, the authors in [24] question the assumed EROI in the literature, implying that their greenhouse gases (GHG) emission rates are likely higher than those of fossil fuels. Besides, the limits might be even more strict due to the multiple uses that land has to meet, namely food growing and dwelling space [49]. Finally, the limitations to wind energy are stressed in [23] following a top-down methodology claimed to be new and leading to an estimate of wind energy extractability less than ten times the minimum previous estimate, and insufficient to supply a 100% RES economy. The question is, then, what the alternative would be. The answer varies under two main strands: (1) downsizing the world economy and population, i.e., degrowth, coupled with climate adaptation policies possibly including weather engineering, or else, (2) denial of both climate change and limits to growth, and go on in a business-as-usual mode (BAU) based on fossil fuels; a range of in-between solutions, possibly involving some amount of renewable and nuclear energy but definitely fossil fuels, could conceivable be pondered as well.

These alarming results have been closely scrutinized in the literature. RE and green growth supporters globally conclude that they are unfounded and derived under extreme assumptions. It is, nevertheless, true that RE supply is subject to uncertainties, if only because climate change will alter the current patterns of rain, wind, and even sun, jeopardizing even the ability to supply RE from existing investments; see Section 3.3 for details.

2.4. Availability of Critical Raw Materials

On a similar neo-Malthusian tack, several authors claim that critical raw materials required for massive scale deployment of REs are in short supply, e.g., [27]. They also claim the adequacy of Hubbert's model to tackle this issue [28]. The so-called peak oil theory introduced by [50] and fitted to US oil data by Hubbert [51], although less far-reaching than [22], yields similar conclusions: a simple logistic model is supposed to portray the behavior of oil production, and of many other raw materials for that matter, implying that after the peak, it decreases relentlessly until exhaustion; see Appendix A. The proposed answers vary greatly: the authors in [48,52] simply suggest a consumption restraint on fossil energies because REs are not the solution; the authors in [51] proposed a massive switch to nuclear power that would supposedly allow for sustained growth; the authors in [53] claim that REs are limited and cannot even support the existing economic and population levels—see Sections 2.3 and 3.4; downsizing the world economy and population would, then, be the only solution. Although that downscaling could, in principle, and arithmetically, be achieved in a matter of just one generation, it seems hard to achieve practically. Nevertheless, even the club of Rome [43] and the report to the US Carter presidency suggested this possibility [42].

Other studies have looked carefully at the problem from a more moderate standpoint, e.g., [54,55], emphasizing the likely limits, nevertheless. Finally, the authors in [56] report more moderate results again, although underline the significant uncertainty involved as well. Nonetheless, bottlenecks and more stringent supply limits are likely to appear, and methods to address them based on recycling techniques and new replacement materials are underway: e.g., recycling linked to automotive design [57] and new developments in scientific research for alternatives [58,59].

Hubbert's model is discussed in Section 3.4 and related issues in Sections 3.2 and 3.3. It must be admitted that there is still much uncertainty remaining concerning material and general planet boundaries, though.

2.5. Intermittency and Other Technical Barriers

The most common criticism of REs used to be their cost and related required subsidies, finally falling on consumers and producers. Since the strong and unabating LRs of wind onshore [14] and notably, solar PV [13] energies have brought down costs to competitive levels [15], the criticisms have switched focus. A recent example is [10], who conclude that 100% RES solutions: a) rely on energy savings unlikely to be realized, b) depend too much on biomass energy sources, and, c) do not account for climate changes that could impinge on wind and hydro-energies. They also assert that they are expensive without mention of LRs. The authors in [60] analyze the 100% RES solution signed by 139 authors [6], concluding that small amounts of battery storage, curtailment, natural gas, and biomass would be required to support a RES solution, so that strictly the 100% option would be unfeasible; see the discussion in Section 4 for further analysis.

Underlying all the previous criticisms are the supposedly overwhelming hurdles of REs intermittency and lack of cost-effective storage solutions to make up for it, so as to match mostly unpredictable and unmanageable demand fluctuations. Since, although still costly, many solutions have been provided for those twin hurdles, criticisms target interannual weather fluctuations and seasonal storage [61].

As will be discussed in Section 3.5, intermittency has been overstated, and there are many solutions for storage, either already available or else being developed and quickly becoming competitive at market prices because of strong LR effects [62,63]. Demand-side management (DSM) measures also have great potential, although they have not been fully implemented yet.

2.6. Transportation, Land, and the Speed of Transition

Some related issues concerning the switch to a low-carbon economy are, at least, the transportation system, the required speed of transition, and land availability. Firstly, and although the substitution of fossil energies has been mainly researched in the electricity sector, the transportation system being based primarily on oil involves more challenging issues. It may be questionable in the first place if it is even possible to introduce electric vehicles (EV) at the massive speed and scales required, if only because raw materials needed for batteries may be in short supply—see Section 3.4. Plus, in particular, air-flights, although not the main carbon emitters, seem almost impossible to run on non-fossil fuels entirely. Secondly, the required speed of transition to a deep low-carbon energy system, be it one hundred per cent renewable or not, is a more than ever pressing issue. According to the IPCC, the upper bound to carbon and GHG emissions generally, at current trends, lies just ten years away in 2030 [1]. Whether this is economically, and even politically and socially possible is another issue for concern. Third, a last and closely related question is land availability. This might impinge on the feasibility of relying on biomass and biofuel energies generally, given that the land requirements will compete with the needs to feed a vast and increasing world population; see, e.g., [49] and the discussion in Appendix B.

The previous account, finally, does not close the set of relevant issues concerning the low-carbon transition, and some of them will be analyzed in the discussion Section 4; specifically, the possible role of nuclear energy, the stranded assets issue, and the justice of the transition.

3. Assessment of Proposed Solutions

3.1. Free Markets Cannot Work Under Oligopoly Power

As for the first criticism, i.e., the merit order effect leading, eventually, to zero market prices, they contend additionally that subsidies are finally paid by consumers [34]. However, this runs counter to the assertion that REs frequently drive prices to zero; since energy markets are generally integrated vertically, i.e., production and retail distribution businesses are owned by the same firms, what is lost in the generation market is recovered in the retail distribution market. This can be easily seen, e.g., in [33]: a merit order effect is supposed to decrease electricity prices by 5 USD/MWh when in fact, they rose by 40 USD/MWh from 2009 to 2014. Besides, lower electricity prices brought by REs may smooth their acceptance and integration thereby, as noted by [64]. However, this discussion is becoming quickly outdated since REs are becoming increasingly competitive, notably onshore wind and solar PV, given that their strong LRs—(20%, 22%) for solar PV, (9%, 10%) for onshore wind—do not show signs of abating. Indeed, a recent study has shown that PV electricity is cheaper than the operating variable costs of at least half of the coal plants in the US [15]. Thus, the LR is driving down total REs costs, including capital expenditures and below variable fossil fuels costs. Since soon, no subsidies will be required anywhere, REs will enter the market at their true LCOE, which will become the market price provided free market competition is preserved. Note that precisely this is what was required by critics of the RES solution [16].

In the long-run, competitive equilibrium transitory misalignments of supply of demand will be adjusted through price changes, and more permanent demand changes through supply adaptation. This is the standard working of a free competitive market. As for intermittency, the increasing penetration of REs in several markets and a host of research show that up to 80% of RE electricity supply can be accommodated without any significant changes [65,66]. Besides, there is no shortage of storage solutions, many of them becoming quickly competitive through strong LRs; see Section 3.5.

It should be pointed out finally that perhaps the most severe threat to the deployment of REs, similarly to many other economy sectors [67], does not come from the market itself. Rather, it derives from the vested interests of the incumbent fossil energies that have managed to distort competition through oligopolistic behavior; see, e.g., [11,68], in particular [69], for a model of the capture of regulatory bodies by oligopolies, and [70] underlining how democratizing the energy market harms the oligopoly incumbents.

3.2. Limits to Green Growth

That the earth is bounded is an inconsequential statement unless those limits are actually binding, as several authors suggest that they are. Economics has always answered that human ingenuity through research and development (R&D) will yield new discoveries and solutions. As a remarkable example, the authors in [71] stated that the [42] report was an outstanding case study in abusively portraying a planning and forecasting exercise as actual scientific truth, the main underlying argument being that those forecasts broadly ignore the impact of technological change and human ingenuity. Some have even suggested moving massively to another planet, possibly Mars, to avoid stalling growth, a proposal that has been dismissed by a leading British astronomer as unrealistic [72].

Looking at history, conclusions are not reassuring. In an extensive study, the authors in [73] assembled evidence on the failure of many past civilizations as a result of increasing societal complexity derived from the problem–solution drive behind all of them. This may have been due to some material resource exhaustion, or to other explanations; the work [74] even suggests that if aliens existed and given that we have not been made contact yet, that would imply the possibility of civilization extinction applying to humans likewise.

As for the report in [22], in retrospect and according to [75], the BAU scenario has forecast adequately critical features of 30 years of historical data, although it has underestimated GHG emissions and ecosystem limits already at risk [76]. The threat and dire consequences posed by general decreases in biodiversity have increased lately, as reported in [77]. Another prominent example of the earth's limitations is the rise in number and variety of zoonotic diseases as reported, e.g., in [78], something that had already been predicted by a wealth of research and was published as early as in 1994 [79]. Similarly, the authors in [80] underline the current validity of the approach in [22], and suggest abandoning material growth as the guiding principle of economic policy to avoid sudden unplanned collapse.

Other relevant results agreeing with the forecast of [22] are provided by [81]: under BAU, implying a world population of 10 billion, productivity increases following historical trends and unchanged consumption patterns, an extra 600 m hectares (h^a) of agricultural land would be required in 2050 to feed the world population, approximately twice the size of India, which is unfeasible. On top of that, the 10 billion world population projection looks somewhat optimistic under straightforward statistical scrutiny; see Appendix B: a simulation of the expected population value under realistic GDP projections yields a value of 13.4 billion. What is more, there is a 20% probability that the expected population reaches as high a value as 22.3 billion—see Table A1 in Appendix B. The supply availability of raw materials and RE might also set some specific limits on growth; see Sections 3.3 and 3.4.

Taken to the extreme the neo-Malthusian approach leads to grim conclusions: adaptation to climate change, population reduction, and across the board society downsizing [53]. Population control programs were implemented as a follow-up to the report [42], and recent publications by the Club of Rome give similar hints [43]. However, whether well-founded or not, those programs have not been successful, and most have been abandoned. Others argue that population will stabilize by itself as a result of increasing living standards (UN), although the statistical analysis questions that conclusion; see Appendix B. Regarding the availability of RE and although the foundations of the neo-Malthusians' analysis might be questioned somehow—Section 3.3—there are worrying signs that the world is hitting some boundaries, the carbon in the atmosphere being a case in point. In a more positive mood, the authors in [22] and [44] point to solutions based on switching the focus to intellectual activities. An additional issue is that the switch to renewables is also advisable for economic and political reasons [82]; see Section 4. One final implication is that even accounting for technical progress, complete decoupling of growth from material limits and notably, from population growth, as shown in Appendix B, is unfeasible. This would jeopardize the green growth proposal of, e.g., [83], even if there were no limits to RE availability and deployment.

As a short summary, the research of [22,43,75], and the [42] report, did not account for the replacement of fossil fuels by non-exhaustible RE sources, and may have made rather conservative assumptions about technical progress considered broadly. Yet, and although they did not foresee either the overwhelming risk of climate change and other risks like bio-diversity decreases and increasing plagues, the general principle of the building methodology remains valid: there are inescapable constraints imposed by the earth boundaries, be they already known or unexpected for the time being.

3.3. Limits to RE

The RE solution to counteract climate change and stalling GDP growth counts on unlimited supplies of RE. Possible boundaries analyzed in the literature, specifically to solar PV, wind onshore and offshore, and biomass, are discussed next.

The authors in [25,26] argue that the land required to power the world with solar PV energy may not be in short supply. They assume that total demand should be met with electricity produced in the least sunny month of the year, and that up to five times the aggregate demand would have to be stored. In fact, experience and several careful simulations show that there are no special storage requirements up to 80% REs penetration [65], and less than 10% back-up is needed for a 100% RES system [84]—6% according to [66]. That is, although supplying the entire energy demand with solar PV may prove hazardous, it is not required as there are complementary RE sources—notably, wind and even biomass. Other strong assumptions are: (1) module efficiency is assumed 12%, when it is known to be close to 20%, and higher values than 40% have been achieved in laboratories; (2) a 65% performance ratio, when the lowest published value is 90%; (3) extremely low capacity factors, e.g., for two sunny locations such as the south of Spain and Italy, 9% and 12%, respectively, are assumed; in contrast, IRENA [5] gives 20% for the world average, rising to 25% in 2030.

Results on PV land requirements and availability are discussed next. Line 8 in Table 1, in particular, reports the % of the world desert land required to support the PV energy forecast in both RMs put forward by IRENA [5] and the IEA [2] in 2050; in the worst case reported in column III, it turns out to be less than 4%.

Table 1. PV Land Requirements.

	PV Land Requirements		
	I	**II**	**III**
1—h^{a} per MW	1	1.5	2
2—Capacity factor	0.25	0.2	0.125
3—Storage	-	20%	40%
4—Curtailment	-	20%	40%
5—% of earth's land 1	0.296%	0.799%	2.32%
6—% of desert land 2	2.13%	5.76%	16.72%
7—% of desert land 3	3.57%	9.65%	28.0%
8—% of desert land 4	0.48%	1.30%	3.77%
9—% of earth's land 5	0.42%	0.605%	0.82%
10—% of desert land 6	3.02%	4.35%	5.92%

Notes: earth's land 150 m. km^2. World Energy Demand (WED) (2050): IRENA, 350 EJ year (=97.2 PWh). World Energy Demand (2050): IEA, 14,000 Mtoe year (=162.8 PWh). Storage and curtailment, as additional land required in %. Desert land, excluding the Arctic and Antarctic caps, 20.8 m km^2. (1) and (2) Total WED supplied by PV energy (IRENA's WED estimate). (3) Total WED supplied by PV energy (IEA's WED estimate). (4) World PV power (average forecast of IEA's and IRENA's RMs 17.5 PWh/year). (5), (6) PV capacity 63 m MW [8] column 1; columns 2 and 3 increased accordingly.

IRENA has updated their 2016 study [5], projecting a slight decrease in total WED from 350 to 330 EJ per year, implying no significant modifications to the previous results in Table 1. From the several additional RMs considered here, reference [8] might be worth commenting on, given its far more substantial reliance on PV energy than the remaining RMs. The authors in [8] forecast a 2050 WED of 135 PWh, 69% of this total being supplied by PV, i.e., 93.15 PWh. This is just marginally smaller than the 97.2 PWh of WED assumed in the IRENA RM. Therefore, the equivalent values for earth and desert land under the different assumptions considered in columns I, II, and III in Table 1 would be close and slightly lower than those in lines 5 and 6, respectively. The required installed PV capacity in [8] for 2050 would be 63 m MW, implying a 16.8% overall capacity factor—IRENA forecasts values above 20% in the near future [5]. For this PV installed capacity, the last two lines, 9 and 10, in Table 1, give the required land under the different assumptions considered. Again, under the worst case scenario of column III, the required land is lower than 6% of world desert land.

Land requirements are, therefore, mild, and more to the point, available desert land is evenly distributed all over the world; see Figure 4. Turning to the available wind energy, Table 2 reports the most relevant published estimations.

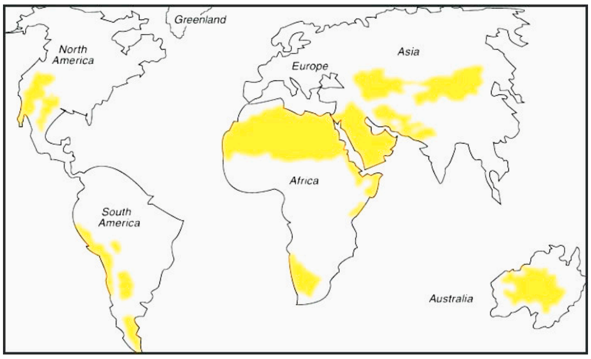

Figure 4. Distribution and land of World deserts.

Table 2. Wind Energy Potential.

	Wind Energy Potential TWh/year	% WED 2050	% WWP 2050
	(A) Top-down methodology		
[23] (2011)	>8760	>6.74%	98.7%
[23] (2011) (corr.)	>70,080	>53.9%	790%
[85] (2010)	148,920–332,880	114.5–256.1%	1679–3743%
	(B) Bottom-up methodology		
	(B1) Low estimates		
[86] (2008)	39,000	30%	440%
	(B2) High estimates		
[87] (2005)	627,000	482.3%	7069%
[88] (2009)	840,000	646.1%	9470%
[89] (2012)	3,504,000	2695%	39,500%
	(C) Saturation wind power potential		
[90] (2012)	350,400	269.5%	3946%
	(D) Conclusion: final acceptable estimates range		
	70,080–350,400	53.9–269.5%	790–39,500%

Notes: (1) WED RMs (2050) 130 PWh/year. (2) WWP (World Wind Power) average RMs (2050) 8.87 PWh/year.

First, the authors in [23] claim to implement a so-called top-down methodology that essentially amounts to starting with an estimate of the total kinetic energy in the atmosphere and apply a series of increasingly reduction factors, *fs*, technical and economical, reaching a final achievable value less than 1 TW. The following comments are in order: (1) $f1$ is derived under the assumption that just 200 m above sea level of available wind can be captured; however, nowadays, turbines higher than 200 m are under construction, and many wind parks are sited at higher altitudes precisely to capture high winds; therefore, this coefficient could be doubled at least. (2) $f3$, the percentage of wind assumed to interact with turbines is only 30%; but turbines can be placed at different heights, and therefore, this coefficient could be taken as one rather than 0.3. (3) $f4$ assumes that only half of the available wind can be extracted profitably; given the unabating and robust cost LRs as noted previously, there is no reason why it should not be 1: here, 0.7 is taken. Implementing these corrections, the final value is 15 TW rather than 1 s line in Table 2.

The authors in [90], updating previous research in [87], take issue with those results, and run a detailed simulation of the available wind according to a model of atmospheric behavior. They give an estimate of 80 TW at 100 m over land plus coastal ocean outside Antarctica; they also consider several of the corrections deemed appropriate to [23] (the f factors). Finally, this last figure is halved to 40 TW to account for economic viability. More to the point, they show that energy extracted at different atmospheric layers does not interact: in other words, the energy extracted up to 80 m has no relation whatsoever with the energy available in the whole atmosphere for that matter. Then, it makes sense to consider only the available energy in the layer just above sea level rather than start from a global estimate of kinetic power in the atmosphere. Therefore, the standard bottom-up approach would be correct, and the top-down methodology in [23] is not, according to them. A further result is that in the next layer up to 200 m, available energy is 250 TW so that the efficiency would decrease before reaching that value. However, before that, it makes sense to apply bottom-up methodologies to estimate wind energy potential. Finally, in [90], the results are solidly grounded on detailed and complex computer modeling of the atmospheric behavior and are, therefore, the most reliable.

The finally acceptable range, excluding the extremely low values of [23,85], and the equally extreme high [89], yields the range (53.9%; 269.5%) of WED satisfied for the 2050 RMs considered. As for the wind power forecast in the RMs [2,5], the outlook is far more encouraging, yielding an interval for the available power of 8 to 40 times the forecast power. As a further example, the authors in [91] show that with coherent GIS-based land scenarios, just 1.4% of PV dedicated land would meet the 2016 European electricity needs three times over, and equally, for 16% onshore wind. Although these values are encouraging, uncertainties remain as to the profitability and capability of wind power to meet world demand at large scales. Besides, there are unforeseen uncertainties induced by climate change, given that increasingly warm weather is expected to reduce the available wind [49,61].

The only case where this type of criticism may have more ground is regarding biomass and other land-grown energies. The authors in [24], for example, argue that their assumed EROI is overstated and that they might emit more GHG than equivalent amounts of fossil-generated energy. Nevertheless, the demand forecast for this type of energy in all available RMs is moderate. What is more, just 10% of total energy would be enough to support the flexibility required in a 100% RES according to [84], and that biomass can supply; see Section 3.6.

Finally, all REs together should be looked at jointly, rather than one at a time. Mention should also be made of untapped RE sources as well, like geothermal and ocean energies that although nowadays, are costly and challenging to extract offer a vast potential [92].

3.4. Resource Depletion

A well-known early resource depletion model was proposed by Hubbert [51] as a logistic function of time; see Appendix A. This function may portray different profiles, as shown in Figure 5.

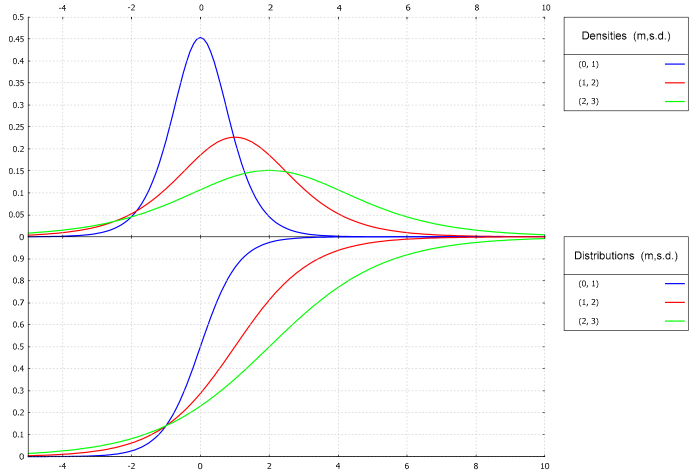

Figure 5. Profiles of the logistic distribution: mean (m), standard deviation (s.d.).

Hubbert [51] claimed that the behavior of oil production follows this precise pattern promoting nuclear energy as a replacement, asserting that it would be so abundant as to make it 'too cheap to meter'. We know that nuclear power nowadays, even after 70 years, is still far more expensive than conventional energy [93]; see the discussion in Section 4 for a fuller account on this point. Depletion models, finally, fit adequately historical data but yield unreliable forecasts; see Appendix A.

Regarding critical raw materials, a recent study [94] focusing mainly on batteries and EV concludes that only cobalt may be scarce and become politically sensitive, since extraction and refining are concentrated in just two countries—Congo and China. Their study assumes that demand for EV increases massively first, and ends in 2025, so that there would be much uncertainty remaining beyond that date. A more recent study [95], although limited to Europe, concludes similarly that only cobalt may be scarce. Reference [7] reaches a similar conclusion at the world level, noting that only lithium and cobalt for electric batteries may be in short supply. Before closing this discussion, the efforts by several mining private companies to extract cobalt, in particular from the deep-sea bed, should be noted, as, in fact, they are securing mining rights in some countries, notably the UK. Although preliminary explorations suggest that, indeed, there might be rich cobalt deposits in the deep ocean, it is also true that they are located inextricably intertwined to clusters of rich biodiversity and other ocean developments not yet sufficiently well understood, and whose destruction might potentially have devastating consequences; see the recent report in [96].

Another recent and broader study [56], based on a thorough assessment of the literature, concludes that estimated values for several metals and renewable technologies vary widely, and that, in particular, the so-called rare-earths are abundant, although their extraction costs might be high. Similarly, reference [97] claims that the price spikes before 2010 in rare-earths were due to China's export restriction, which led to overinvesting in mining abroad, causing a price collapse in 2012; then, there would be no shortage but rather temporary lack of investments. Regarding solar PV and wind energies, the authors in [56] note that there are no anticipated shortages for the supply of required metals in the literature. Besides, all existing surveys and results are derived assuming a zero-recycling rate, and efforts to address this problem are underway; see, e.g., [57–59]. The primary shortages are forecast in materials required for batteries and EVs, a hurdle that may require a redesign of the transportation system as explained in [29,30]. This sets upper bounds on the volume of EVs that can be supported with batteries, so that it would make sense replacing private with public transport, and road by railway transport, which is easily electrified—goods and people. Case studies reporting the benefits of electrified public transport are regularly being published supporting this approach; see, e.g., [98,99].

The eventual discovery of new substitutes, materials, and technologies should not be underestimated either. The authors in [56] point to an array of foreseeable difficulties, nevertheless: (1) rare-earths are at present very concentrated in just one country, China, implying geopolitical risks; (2) the exploration and likely discovery of new resources will likely have huge economic impacts on underdeveloped countries, which will have to be carefully managed; (3) bottlenecks and temporary price hikes are likely to show up in final prices of renewable capital—PV modules and turbines; (4) new demands may arise, particularly regarding the new services economy, a clear example being bitcoin [100]. Studies by the European Union (EU) similarly conclude that there is much uncertainty but that in the foreseeable future, only temporary bottlenecks are to be expected [54,55].

As for other materials required beyond RE investments, phosphorus, an essential soil fertilizer with unknown replacement, may also be in short supply in some decades [101]; it should be underlined that this sets upper bounds on the amount of food and therefore, population, and also bioenergy. Regarding other metals, the authors in [102] highlight the substantial increase in mining and consumption in recent decades and the absence of efficiency increases. For critical minerals like iron, copper, and bauxite, the years remaining at present trends would be 72, 53, and 124, respectively.

Before ending this discussion, the work of [103] on general availability and consumption of material resources at the world level must be assessed. According to them, currently, the world consumes 20 tons of material resources per person and year, and this must be halved to be sustainable. In addition, the world population level should not surpass the 10 billion upper bound, so that total material consumption should be 10 billion tons per year at the most. The 10 tons per person and year can be broken down into 2.2 of biomass, 2.3 fossil fuels, 0.8 metals, and 4.5 minerals. In a renewable-powered world, fossil fuels would be zero and also, most of biomass, given that it is mainly used for cooking and heating; this would leave 6 to 7 tons of annual material consumption per capita. Recycling would add further slack to the upper bound as well. The authors in [103] remark, nevertheless, that in order to achieve that halving of consumption from 20 to 10 tons, massive efforts in consumption styles, efficiency increases, waste reductions, etc., must be achieved. The authors in [103] conclude, finally, that not just growth, but also green growth is jeopardized by material availability. Since this research was published in 2011, later research [102] has identified supply availability limits for some metals and other materials. However, several years of supply are still available without accounting for recycling and substitutes as yet. The risk implied by eventual population increases larger than commonly accepted should not be overlooked either; see Appendix B.

Three final working conclusions may be: first, the biggest challenge lies in the transportation system, so that a profound overhaul is required; solutions are available [29,30], although they may not be easily implementable. Second, no further immediate shortages in critical materials are foreseen, notwithstanding the high uncertainty remaining regarding future dates. Third, jointly with the discussion in Sections 3.2 and 3.3, these resource limits set bounds on material growth, even if based on RE, i.e., green growth. The implicit conclusion is that the unfeasibility of any positive growth might not be wholly warranted by available research, since technical progress will always present opportunities, however limited. This by no means implies that unfettered material growth is feasible, or even desirable. As noted in Section 3.2, the problem is more one of replacing a short-sighted target of well-being as measured by the market value of goods and services, i.e., GDP, by a broader definition of prosperity accounting for intellectual and related activities, not so easily measured by market prices.

3.5. Storage and Intermittency Smoothing

The two more significant hurdles for RES, and especially so for the one hundred solution variant, may be the twin problems of intermittency and storage. Considering first intermittency, it may have been overstated: the authors in [104] note that capacity factors for wind onshore/offshore are 30%/50%, whereas for coal, it is below 60%; according to [105], spells of 10/15 days without either wind or sun in Europe happen only once every five years, i.e., $(10, 15)/(365 \times 5) = (0.5\%, 0.8\%)$ of the time, requiring just a minor demand adjustment rather than massive storage facilities. Second, supply-side solutions abound: interconnections of large areas and adequately diversified portfolios of REs over two or more energy sources smooth high and medium variability effectively; portfolio theory can also be implemented to distribute geographically combinations of different REs to reduce variability [106]. DSM policies are less well tested, but there are many recent encouraging results: the authors in [107] find significant price elasticities in the medium and long runs, and the authors in [108] point that it may just take informing consumers adequately. Additionally, as noted by [109], consumer preferences are dependent on available infrastructure, implying the feasibility of wide demand pattern changes, provided the right investments are conducted.

As for storage, it must be reminded that this is a hurdle for fossil energies as well [110]: coal and nuclear energy are hardly dispatchable at short notice, requiring storage beyond supplying the minimum constant demand. In fact, the first pumped hydro storage (PHS) facilities were devised precisely for this reason [111]. Besides PHS, an array of well-known solutions are available, some suitable for the short-medium term, like batteries, and others for seasonal storage [112–114]. In fact, the survey in [113] concludes that no energy storage technology is uniformly the best, some being more suitable than others depending on the case. More importantly, the authors in [113] also conclude that barriers to storage are not technical but rather economical and regulatory. Since that survey was conducted before 2016, the outlook in both regards has improved and continues to do so. This squares with the results reported in [62], where nearly 17% LRs are reported for lithium and other types of batteries. The authors in [62] are careful to underline, nonetheless, that the available sample is short, and other limitations of the study. The authors in [63] report similar results underlining the role of research as well.

Some of the storage techniques that outstand are Compressed Air Energy Storage (CAES) and power-to-gas (PtG) of different kinds, including hydrogen, and in particular, they are suitable for both short and seasonal long-term storage [66]. The CAES, a technical solution that has been known for some time, could also partially replace batteries in EVs, which is one of the most significant barriers to the overhauling of the transportation system [115,116]. Finally, there is another simple and intuitive storage technology, namely 'gravity-storage', which is also the principle behind the PHS: many technical solutions for large scale implementation are available [112], although cost and available proper locations are obstacles to be overcome.

A closely related issue is the amount of storage required for a complete 100% RES. An early study found that for up to 40–50% RES penetration in the electricity system, no further arrangements beyond the existing flexibility mechanisms are required [117]; the authors in [65] raise that value to 80% penetration, implying that a maximum of 20% storage would be required in the absence of other facilitating flexibility mechanisms; reference [84], after a detailed hourly analysis of the German market, concludes that a 100% RES with 10% of biomass energy to ease intermittency would require storage support below 10% of total energy; reference [66], finally, reduces the need for storage to just 6% of total demand. Therefore, it is fair to conclude that the storage requirements for a 100% RES have been grossly overestimated.

The authors in [118], finally, provide an extensive survey of available measures to deal with both issues, intermittency and storage, although climate change may reduce the availability of some storage technologies, namely PHS, and the supply of cobalt may hinder the development of electric batteries; see Section 3.4.

3.6. Proposed Solutions

The IEA [119] views the transformation of the transportation system as an opportunity for further growth led by research and massive EV deployment, downplaying the risk of raw materials supply and supporting a carbon tax to cover the tax-losses incurred because of reduced oil consumption. However, if only because of the unavailability of sufficient raw materials, this RM is unlikely to be realized; see Section 3.4. An early alternative was [29], who suggested an array of measures for a transportation system without oil and its derivatives. These ideas are the foundations of a more complete study by [30], where a thorough evaluation is conducted. The authors conclude that it is technically and economically feasible, requiring an estimated 75 EJ/year and continued investments of 1% of world GDP (WGDP) for thirty years. The energy requirement is less than a quarter of the total energy estimated for 2050 by the IEA [2] and IRENA [5], and the investment is not significant when compared to aggregate world investment figures. Broadly, the new system would be based on massive public electrified transportation and a small proportion of private EVs as well. It should be added that CAES is a technique that could replace electricity and batteries to some degree in private vehicles [115,116]. This would decrease the need for lithium, cobalt, and other critical materials, that although in sufficient supply for the time being, might be scarce in a massive future transformation [94]. Another proposed solution [8] relies on large-scale liquid biofuels extracted from jatropha growing only in degraded arid land, and specifically forecast 260 million tons of biofuel produced in up to 700 million h^a, complemented with carbon sequestration facilities. The authors in [120] underline that given the high uncertainty regarding the cost of jatropha agriculture, there is a risk that this strategy is too costly. Besides, according to [120], it relies on ambitious productivity assumptions that imply a quadrupling of typical oil harvest. Finally, the report does not discuss in detail the sustainability implication of this ambitious expansion of jatropha agriculture; e.g., even arid land is likely to be needed to implement afforestation policies necessary to capture CO_2.

Solutions in the line of [29,30] have several advantages and possibly are the only feasible ones. For example, the benefits of relying on easily electrified public transport in cities have been shown in [98,99], and public transport can also create significant numbers of jobs and stimulate inclusive growth [121].

The speed of transition required to counter carbon emissions is hardly a debated issue beyond underlining its urgency [1]. Recent available results point to the economic feasibility of a fast implementation of IRENA's [5] and IEA's [2] transformation RMs in just 12 years, as required by the IPCC [122]. A more complex issue may be the political and social transformations entailed. Reference [31] argues that, according to historical records, past energy transitions have taken several decades to complete, and that a fast initial penetration is no indication of future speeds. While both observations may be correct, they forget, e.g., the quick transformations, social and economic, undergone in war times by many countries. Besides, what [31] does not discuss are the measures to cope with climate change: it is to be understood that the only dismal solutions, short of massive unplanned extinction, are adaptation, overall downsizing of the world, weather engineering, etc., and keep on consuming fossil energies. It should be admitted, nevertheless, that the issue deserves more—and fast—sociological research. Yet, even assuming feasibility, the authors in [123] note that historical energy transformations occur after the discovery of a cheaper energy source, leading to large increases in growth and energy consumption. Because of several physical limits—see Sections 3.2 and 3.4—that path should be avoided. As a final comment [43], note that the quick, coordinated, and effective world response to the diminished ozone layer in the 1980s is proof of the feasibility to face an unexpected and overall world challenge. The quick and drastic responses to the COVID pandemic, involving massive lockdowns of millions of people across the world, would be further additional proof.

A remaining issue closely related to energy transformation is the need to feed an increasing population, and, therefore, the ensuing land requirements that may compete specifically with biomass and other related forms of energy [49]. That it would be technically feasible to sustain the current world population by simply shifting meat to vegetables consumption just to meet nutritional needs, eliminating all food wastes and losses, and without producing more food, is shown in [124]. A less radical approach is taken in the detailed research of [81] that under mild assumptions concludes that it would be possible to feed 10 billion people with a land area roughly equivalent to that of India. In their most ambitious scenario for 2050, (a) land productivity increases 50–70% based on R&D, (b) ruminant meat consumption decreases 30%, (c) food losses decrease 50%—1/3 of total food is currently lost—and, (d) bioenergy other than based on residues and wastes is reduced to zero. These are not too stringent requirements and would result in 800 million h^a freed for reforestation, which, coupled with other measures, would reduce agricultural GHG emissions to zero. Perhaps the most ambitious assumption is the productivity increase on which all other results hinge. Additionally, solving the intermittency of REs would become harder without the bioenergy assumed in many existing published RMs [2,5,6,84], although there are some RMs proposals based on 100% RE without either it or bioenergy with carbon capture and storage techniques [7]. A hard to overcome hurdle would likely be the firewood and charcoal used for cooking in underdeveloped countries, near 15 EJ/year according to FAO [81] and equivalent to 4% of the total energy demand forecast in 2050 [5], although that should be replaced because of health issues anyway.

4. Discussion and Further Questions

4.1. The Nuclear Energy Debate

Since save for a handful of mainly academic transition RMs, most policy-oriented plans developed by relevant world institutions rely, to some extent at least, on nuclear energy, and this being a highly controversial issue, a short discussion is in order. Nuclear power was first put forward by [51] as a solution to the dwindling oil reserves formalized in the peak oil paradigm. The authors in [51] went even further to suggest that nuclear energy would be akin to manna becoming 'too cheap to meter', and therefore, fueling growth and prosperity. Seventy years of deployment and discussion, however, have disproved that forecast. As noted in [125], cost overruns in nuclear investments are the norm, being between two and three times the initial projected cost. This, however, seems to be a feature shared by all large industrial investments, as remarked in [126]. Another drawback is that the LR of nuclear projects after 70 years has remained stable or even increased, which compares unfavorably to the relentless cost decreases in renewable energies, notably solar PV and onshore wind [126]. All this boils down to an LCE roughly double of current electricity prices, and far more costly than other energy sources [93]. Nuclear energy is also beset by a host of well-known related problems, like breakdowns, and notably, residuals disposal. Technical hurdles to the development of other potentially far more efficient versions, such as nuclear fusion, are also fraught with problems [127]. Notwithstanding all these issues, nuclear energy may provide energy independence and security, the French example being a case in point [126], is a relatively clean energy source, and although not strictly renewable, it may provide a huge energy source virtually inexhaustible provided the fusion technology comes to fruition. Besides, the cost of a particular energy source, although of primary concern for individual investors, is less relevant from a system's point of view: what matters systemically is whether it increases or decreases the overall cost of the system, and nuclear energy may provide a back-up that reduces the requirement for alternative and possibly more expensive solutions [128,129]. It may also be required to support an otherwise 100% renewable system, according to the detailed estimation reported in [130]. These are also the justifications behind the requirement that nuclear energy should be publicly owned if it is supported. Finally, all of these motives explain why, although being in decline, many countries are reluctant to drop it entirely, and most low-carbon RMs count on it.

4.2. The Stranded Assets Issue

According to the most recent estimates [131], the potential value of SA in the fossil industry can be broken down as follows: 10 trillion (tr) USD in upstream extraction and distribution, 22 tr USD in downstream demand, 18 tr USD in equity and another 8 tr in debt. The World Bank (WB) [131] also estimates total reserves of 900 tons of coal, gas, and oil valued at 39 tr USD. This last value is somewhat higher than the aggregated financial value of 26 tr USD—18 tr equity plus 8 tr debt. Since financial valuations, at least theoretically, are meant to reflect reliably the current discounted value of all future net profits generated by available physical capital—machinery and mineral stock reserves—this last estimate looks closer to a correct valuation. The total market value of potentially SA would add up, therefore, to 58 tr USD—$(10 + 22 + 18 + 8) = 58$, tr USD of 2019. This is the value the fossil industry would stand to lose as a result of policies designed to replace it with a RE supply. Since that would be the immediate consequence of policy measures, according to some at least, the question is whether the owners of that capital are entitled to claim some kind of compensation. However, there are essential liabilities neglected in that assessment: first, according again to the WB, the value of monopoly rents above what would have been the otherwise standard competitive market profit rate, amounting to an average of, at least, roughly 1.5% of WGDP over the last 50 years, the total final amount being approximately 30 tr USD at current rates—estimated average WGDP in the past 50 years 40 tr, so that $(40 \times 50 \times 0.015) = 30$; data before 1970 are not available and is taken as zero.

The accumulated value of CO_2 emissions in the past should be accounted for as well. CO_2 degrades with time and is also absorbed by the land and ocean. It has been estimated that this process lasts for about one hundred years [132]. One first estimate would then be the straightforward accumulated sum of all emissions in the past one hundred years, leading to an assessment of 1482 billion of tons. Since, as noted, CO_2 degrades with time, it could be argued that only outstanding total accumulated values should be accounted. Then, several decreasing schemes could be implemented, a simple solution being a continually decreasing rate such as:

$$AcCO_{2_t} = \Sigma_{s=0}^{99}(\delta^s \times CO_{2_{t-s}}) \quad (1)$$

where $AcCO2_t$ is the accumulated value of emissions at time t, and δ the appropriate decreasing rate. For values of δ ranging from 0.9 to 1 in steps of 0.02, the above expression in (1) yields the corresponding values of (314, 377, 469, 619, 892, 1482) for $AcCO_{2_t}$—all billions of tonnes. Finally, a value for δ of 0.9 yields a weight equal to 0.35 after just ten years, implying possibly a fast degradation rate. As for the cost of carbon, the authors in [133] suggest in their survey 7.3 tr USD/tCO_2. This can be taken as a lower bound since, e.g., [134], suggest a carbon tax for the next 30 years between 50 to 100 USD, which is the estimated value required for the markets to replace fossil with RE sources. Taking an average value of 0.94 yields 469 billion tons that valuated at an average price of 50 tr USD boils down to an estimated amount of 23.4 tr USD. Adding all liabilities finally—30 tr of monopoly rents and 23.4 tr of accumulated CO_2 emission—yields an estimate of 53.4 tr USD. Since the potential SA value has been estimated as 58 tr USD, the final assessment of the rightful claim by the fossil industry turns out to be $(58 - 53.4) = 4.6$ tr USD, i.e., less than 10% of the initial estimate.

As a final point, it must be noted that this discussion has been conducted under the assumption that the demise of the fossil industry is somewhat caused by governmental actions. This, however, is likely not to be the case, since REs are already cheaper than the variable costs of the fossil industry in some cases [15], and are relentlessly becoming cheaper and market competitive without any government support all over the world, driven by high and constant cost learning rates [131]. Then, this would be simply another case of an industry becoming obsolete because of market developments. Notwithstanding the preceding conclusion, it is also true that the loss of such a large amount of assets poses a significant risk to the financial markets and the world economy thereby, requiring early and immediate action to prevent it. Furthermore, another closely related issue is the jobs lost in the process and the justice of the transition, something that should be addressed as it is being tackled, e.g., in Europe [135,136].

4.3. Optimization of RMs Design

Although not all RMs are designed claiming to be the result of an optimization exercise, it is a relevant question to ask whether this should or should not be the methodology by default. Examples of RMs claimed to be the result of optimization are [2,8], and RMs designed following ad hoc criteria suitably adapted to several criteria are [5–7].

There are at least three questions pertaining to the optimization methodology itself, and another one possibly more definitive, regarding the suitability of focusing on a single criterion, being almost always cost minimization. Considering the method itself, a first question relates to the energy demand projections, which are taken as the starting point to design an energy supply RM to meet them. At the aggregate level, future energy demand, say 35 years ahead, is highly uncertain: e.g., [137] in a detailed although not sufficiently publicized study, find that the technically feasible aggregated energy savings could reach up to 73% of current demand; on the other side, future communications and services could expand electricity demand significantly, an example being bitcoin-generated demand, and the lack of significant declines during the COVID lockdowns despite the massive drop of transport traffic [138].

At a more disaggregated level, in order to perform a proper optimization, at least hourly demands are required; however, no such data exist except at very highly aggregated geographical levels, so that most hourly demand profiles are interpolated under more or less reasonable assumption, i.e., they are estimates, not real observations, and therefore, subject to a degree of uncertainty that is never specified; e.g., [8,139]. A second question raised in [140] was the lack of transparency of the optimization exercises. In fact, it is almost always virtually impossible to reproduce the published results, let alone generate new ones with the models claimed. This is partly due to the sheer difficulty of the exercise, frequently involving hundreds of equations and variables and sophisticated computer programs. In addition, a nonlinear optimization setting is subject to the problem of multiple local optima, making it difficult, if not impossible, to identify the overall global optimum. This point is rarely mentioned or sufficiently stressed in the exercises discussed.

A third difficulty relates to the selected optimization criterion itself, almost always the current discounted value of future cash streams somehow appropriately defined. The most common criterion is the monetary cost, although from an economic point of view, it is net profit what should be targeted instead. Then, the synthetic yardstick resembling profit is, in fact, the LCE rather than total cost [122], and that is what should be the focus of optimization. What is even more, when LRs are at play, the only factor that matters significantly for the optimum solution is the volume deployed during a given period, rather than the speed of deployment, or other possible factors like the cost of capital and the like. The upside of this result is that it offers additional degrees of freedom for the timeline design of the RM.

A potentially far more severe shortcoming of those exercises derives precisely from the focus on optimization itself. In fact, there are several additional criteria to be accounted for in the design of such an overarching societal transformation. First, and since one of the main objectives of those RMs is precisely the reduction of GHG emissions, that is a criterion that should be explicitly targeted; this can be done, e.g., putting a value on carbon and other gases, and in a second step, accounting for the cost of emissions appropriately in the design of the optimization setup. However, since the sheer survival of the civilization is at stake, it is hard to put a price on it. Second, justice criteria should also be looked at when designing the replacement of some energies by others, presumably located at different geographical places: jobs and community life degradation should be considered so that the optimum results may be somewhat different; see, e.g., [135]. Third, uncertainties of several kinds should also be considered: this may derive from the unknown future paths of energy costs [122,141], future values of population and economic growth, or even from climate change, that will most likely alter the optimum location for RE facilities, notably wind and hydro. All a planner can do is lay down a clear set of alternatives regarding the several available choices, adequately designed. The final selection and weighting for the criteria themselves is a matter of social preferences, to be determined at some other instance, possibly political—in economic parlance, optimization determines a frontier of possibilities, the final chosen combination being made by the relevant agent according to its utility function.

4.4. Discussion

Intermittency has been overstated, and there are many storage solutions, some not yet fully explored like gravity-storage, becoming cheaper because of LR effects; see Section 3.2. Besides, DSM offers great potential for solving both hurdles, since consumer preferences are conditional on available infrastructure [109] and social institutions [142], thus, providing significant potential for adaptation. Finally, RE costs are continually decreasing because of unabated strong LR effects, quickly becoming market-competitive [15,131,143].

The outlook is less bright regarding investment-led green growth. Although there are no foreseeable boundaries to REs, as discussed in Section 3.3, other limits may prevent it. Depletion models miss some factors like, (a) efficiency increases, (b) new discoveries, (c) recycling, and (d) possible substitutes. In some instances, nevertheless, namely the limits to recycling [57], availability of materials, notably cobalt and phosphorus, land [81], and biodiversity [76], there may be issues that set limits on world population and EV deployment.

Then, according to the downsizing proposal, neither growth nor even the current world economy are sustainable [53]. Recycling would add little growth room [144], and even intellectual growth and related activities are rejected since that would only lead to appropriation by a few [145]. However, beyond some descriptions of the desired much-reduced society, based on spending leisure time with other human beings, direct democracy, and small loosely connected groups, there is not a clear set of measures and RM laid out to achieve the transition; nor is there a detailed discussion of the unsustainability, beyond some general points about current excessive resource consumption; see, e.g., [53,144]. As noted, e.g., by [146], society is unlikely to accept such a proposal, since human beings generally aim at improving their lives, and only measuring it just by the number of material goods owned is what is wrong. According to [146], finally, it would be legitimate to conclude that this proposal is more an extreme political agenda than a sound scientific alternative. Perhaps more research on this subject could clarify the issue.

The prosperity approach [44] rejects both material growth and downsizing. Prosperity is loosely defined as the availability of leisure time and intellectual activities, and RM is not specified, since current economic levels are deemed sustainable. However, there is room for GDP growth—see Section 3—and as remarked by [146], society is unlikely to accept a stationary state.

A more promising and feasible alternative is offered by the Human Development Index (HDI) as a complementary measure of well-being to material GDP introduced by the United Nations (UN) in 1990 [147]. It is intended to capture both material wellbeing and personal development capabilities [148] weighting GDP and quality life indices, notably life-expectancy and education levels. It is updated continuously, and currently, inequality measures are being added.

Another vehemently discussed issue is whether a 100% renewable solution for 2050 is feasible or not, some authors strongly denying it [17,60], while others equally strongly supporting it [6,7]. Other RMs, although not fully 100% renewable, rely mostly on those energy sources, without denying explicitly that after 2050 that could not be achieved; see, e.g., [60]. Yet, to some extent, whether or not this is possible is a secondary concern, and policymakers should focus more on the near term. The proposals derived from the several RMs may not be that far apart. In any case, the general recommendation should be that REs should be deployed as fast as possible, given the urgency implied by climate change, as underlined by the IPCC [1]. Whether or not a fully 100% RE solution is achieved in 2050 or not is a matter for the future to solve.

The RE transition is economically sound [118,141], well-suited to a market economy—see Section 3.1—technically feasible [2,5,6], and also advisable because of security of supply and to balance the foreign accounts of importing countries [82]—notably China and the EU. Significant physical barriers exist though, implying a strong backing for replacing the policy focus from unbridled GDP growth to broad prosperity [22,44], or better, focusing on the HDI [147]. The necessary speed of the transition may be a sociological issue according to history [31], and overconsumption of cheap RE is another potential risk [123]. However, the quick and coordinated world answer to the depletion of the ozone layer in the atmosphere [43], and the decisive answers to the COVID pandemic, at least, in some countries, offer room for hope. Nevertheless, as in other fields of modern societies [67], possibly the main risk arises from the vested interest of influential incumbent fossil energy producers who try to capture regulators and lawmakers [69], finance publicity campaigns addressed to the general public [68] and the scientific community [11], and intend redesigning policies to profit from the new developments brought by the advance of REs [149,150].

Finally, and while many individual societies have all failed in the past, possibly because of a failure to deal with new challenges facing ever-increasing complex structures [73], the world as a whole has not, underlining the feasibility of a solution to climate and related risks.

5. Conclusions

That the power system can work properly in a competitive market environment with a high penetration of REs, even up to 90%, with small amendments seems likely. This is because the intermittency of RE has been overstated and many storage solutions are becoming available. The strong LRs of some of them, including battery-storage, will likely allow the deployment of a new RE power system at acceptable market-competitive costs. Demand management offers great potential too, although its implementation has yet to be shown. Nevertheless, whether a full 100% RES for the whole economy is feasible is another question that may be much harder to realize if only because bioenergy, on which several of the proposed RMs by the relevant institutions rely, clashes with the need to feed an increasing population and reforestation efforts required to counter GHG emissions. Then, it may be that small amounts of gas, or even nuclear energy, may be needed for a significant period of time.

What does not look easily achievable is the green investment-led strong growth currently supported by several institutions, including the EU. Although the amount of kinetic energy in the atmosphere economically extractable and the land available for solar PV parks might both support it, there are other unavoidable constraints. Cobalt, a mineral required for modern batteries, is in short supply and a known replacement is not available yet; phosphorus supply, a fundamental component of fertilizers, might also be compromised in a few decades. Other metals might also be in short supply, although this will not be an issue for some time. Cobalt, particularly, is a clear obstacle to the massive deployment of EV, although well-detailed alternatives based on collective transportation are available. Above all, the world is running on a tight land budget: it is possible to feed a moderately increased population and reforest sufficient land with substantial pattern changes, but not to support unbridled growth.

Some have proposed downsizing as an alternative, which would allow keeping the consumption of fossil fuels for a long time. Others suggest prosperity entailing freezing the standard living conditions at current levels, at least for developed countries. Both alternatives, particularly the first, may not be sufficiently well-founded as some room for material growth exists. Besides, societies generally aim at improving the activities in which they are involved, so that it is unlikely that any of those objectives would generally be accepted. A feasible alternative would combine some material growth as measured by GDP with other measures of well-being and other capabilities of personal development. An encouraging proposal in this line is the HDI supported by the UN.

A final question is whether the transition to such a 100% RES is economically feasible, and history is not encouraging in this respect. Energy transitions in the past have taken decades, leading to increased energy consumption, both features that nowadays should be avoided. Yet, perhaps the main obstacle comes from the incumbent fossil producers, although key financial players are already beginning to withdraw from fossil fuel-related investments.

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Abbreviations

BAU	Business as usual
CAES	Compressed Air Energy Storage
DSM	Demand Side Management
EJ	Exajoule
EROI	Energy Return on Investment
EU	European Union
EV	electric vehicle
GDP	Gross Domestic Product
GHG	Greenhouse gas
HDI	Human development index
h^a	hectare
IAM	integrated assessment models
IEA	International Energy Association
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Association
LCE, LCOE	Levelized cost of energy
LR	Learning Rate
NPV	Net Present Value
ODM	Optimal Depletion Models
OECD	Organisation for Economic Co-operation and Development
PHS	Pumped Hydro Storage
PtG	power to gas
PV	Photovoltaics
R&D	Research and development
RE	Renewable energy
RES	Renewable Energy system
RM	Roadmap
SA	Stranded Assets
UN	United Nations
USD	United States Dollar
WB	World Bank
WED	World Energy Demand
WGDP	World Gross Domestic Product
WWP	World Wind Power

Appendix A. Empirical Resource Depletion Models

The time till exhaustion t^0_{eh} of a given resource at $t = 0$, is given as,

$$t^0_{eh} = \overline{R}^0 / \left(\Sigma_1^{t^0_{eh}} q^0_t\right) \tag{A1}$$

where q^0_t is the expected resource production, or mining, at t = 0. The superscript $(.)^0$ is included to underline the variability of the estimated reserves, $\overline{R}^0$, with time—the literature refers to this as Ultimately Recoverable Reserves. Given an estimate for reserves, $\overline{R}^0$, estimation of t^0_{eh} requires just a path for q^0_t and reference [50] first suggested a bell-shaped path according to observations, therefore, implying a production peak. Later, Hubbert [51] proposed the logistic distribution giving the amount of oil mined over available reserves at t, $y_t = \left(q_t/\overline{R}\right)$, as a function of time—the super index is omitted for notational simplicity. This distribution can be shown to embody a plausible model to explain growth in many instances [151]. The probability density function, $f(.)$, (*p.d.f.*) and its cumulative distribution function, $F(.)$, (*c.d.f.*) are [151],

$$f(x_t) = s^{-1} \times exp(z_t)/(1 + exp(z_t))^2 \tag{A2}$$

$$F(x_t) = 1/(1 + exp(z_t)) \tag{A3}$$

with mean and variance $\left(\mu, \sigma^2\right)$, where $s = \left(\sqrt{3}/\pi\right)\sigma$, $z_t = ((x_t - \mu)/\sigma)$, and $y_t = f(x_t)$. Other probability distribution functions could be implemented [152], typically the Gaussian density since it also displays a similar bell-shaped profile, i.e.,

$$f(x_t) = \left(\sigma\sqrt{2\pi}\right)^{-1} \times exp\left(-z_t^2/2\right) \tag{A4}$$

and z_t as before. For estimation purposes and taking *logs*, the model becomes,

$$log(Q_t) = log(R) - log\left(\sigma\sqrt{2\pi}\right) - \left(t - t_{pk}\right)^2/\left(2\sigma^2\right) \tag{A5}$$

t_{pk} being the time of peak production happening. Since the last term is a quadratic involving two variables $\left(t^2, t\right)$, it allows estimation of the two parameters $\left(t_{pk}, \sigma\right)$—statistically, they are identified. The constant of the equation would allow, then, recovering an estimate for reserves, $\overline{R}$.

An asymmetric density [152] can be obtained straightforwardly by making σ different for different observations, e.g.,

$$\sigma_t = exp\left[-\alpha\left(t - t_{pk}\right)\right], \quad \alpha > 0 \tag{A6}$$

so that σ_t increases before t_{pk}, and decreases after it yielding a thinner right tail, matching casual observation. Total past extracted values, i.e., $x_t = \sum_{s=1}^{t-1} y_s$, could also be used as explanatory more meaningfully. Another direct extension would be to determine empirically which function profile—i.e., logistic, Gaussian, etc.—fits the data better. Further parameters could be added as well, e.g., $\left[\alpha_0 - \alpha_1\left(t - t_{pk}\right)\right]$, in the exponent of (A6). These generalizations would require additional data and, precisely, an initial estimate for reserves. It should be noted too, that functions yielding similar fits may generate wide apart parameter estimates, and that the underlying parameters may not be accurately estimated: this is because statistical fits yield unreliable results for explanatory values departing significantly from the estimation sample—see, e.g., [153]. Finally, other models with similar shapes but departing from the smoothness of density functions and with different slopes before and after peak production could be implemented as well [154].

The preceding models have the advantage of simplicity, but the trade-off is their lack of theoretical basis. The purpose of the Dynamic Systems approach [22] was precisely to overcome that pitfall, by specifying a detailed set of interrelated dynamic differential equations purportedly reproducing economic behavior. Following this approach, the authors in [47] implemented a fully-fledged model to explain resource mining and depletion. A simple model yielding equivalent outcomes is,

$$GDP_t = (1 + \theta)^t \times GDP_0 \tag{A7}$$

$$E_t^N = \delta \times GDP_t \tag{A8}$$

$$E_t^G = E_t^I \times EROI_t \tag{A9}$$

$$E_t^I \equiv E_t^G - E_t^N \tag{A10}$$

$$EROI_t = \alpha - \beta \times \textstyle\sum_{s=1}^{t} E_{t-s}^G \tag{A11}$$

(A7) states that GDP_t grows at a constant rate θ; (A8) that the amount required of a given resource by GDP_t, net energy in this case E_t^N, is a constant proportion of GDP_t, δ; (A9) is implied by the definition of the $EROI_t$, E_t^G, E_t^I, being, respectively, gross energy obtained by the energy invested; (A10) is the identity relating the various energy definitions, and (A11) implies a linear decrease for the $EROI_t$ as the finite available amount of the resource, energy in this case, decreases. Other EROI behavior could be implemented, particularly the bell-shaped pattern assumed by [51], yielding more realistic behavior with similar end results.

The approach of [22,47], although loosely representing economic behavior, is not derived explicitly from optimization contrary to what some economic theory assumes. Theoretical models derived from explicit optimization, i.e., optimal depletion models (ODM), can be obtained, e.g., maximizing the net present value (NPV) of all future income streams discounted to the present, i.e.,

$$NPV_0 = \int_0^\infty [p_t q_t - c(q_t)] \times e^{-\delta t} dt \tag{A12}$$

where p_t is the price fetched by the resource in the market at time t, $c(q_t)$ its extraction cost function, and δ the time discount factor. For standard cost functions, this yields smoothly declining production time-paths, contrary to observation. This can be amended by introducing a more complex cost function of the type, $c(q, R_t, t)$, where the cost increases with resource depletion, R_t being remaining reserves, and increases with t. Reference [155] shows that this can yield a bell-shaped behavior matching actual data.

ODM can similarly be written in discrete form, a procedure that allows deriving an econometrically estimable equation. Reference [156] gives an example as the result of maximizing,

$$NPV_0 = \textstyle\sum_0^\infty [(p_t q_t - c(q_t, R_{t-1}) - w_t D_t) \times d_t] \tag{A13}$$

where $d_t = (1+r)^{-t}$, r is the rate of interest, D_t discoveries in t, i.e., $R_{t-1} = R_t - q_t + D_t$, and w_t their unitary cost. The optimization can be set up as well as the discounted sum of conditional expectations on available information at $t-1$; see [156].

Although the empirical fit of all these models to available data has broadly been accurate, their forecasting performance has not been so successful, a frequent feature in econometric estimation; see, e.g., [153]. Nevertheless, they have been useful to underline resource exhaustion and the implied complexities to overcome them.

Appendix B. World Population Projections

Appendix B.1. Statistical Models

According to recent population projections conducted by the UN, population is expected to stabilize around 11 billion in 2050; see [132] for further references and discussion on the points analyzed here. This is frequently based on a straightforward inspection of population increase along time: since its rate of growth—red line in Figure A1, set on a continuous downward path after peaking at 2.2% in 1968, it apparently lends base to the conclusion that, indeed, population is stabilizing and eventually, the rate of increase will reach zero. However, by looking at the raw increase, i.e., the year-on-year increase—the blue line in Figure A1, the story is different, showing a constant rise and implying a linear albeit not exponential growth for the population level.

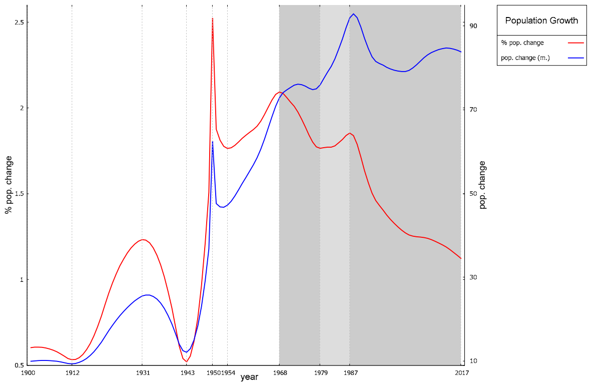

Figure A1. Population growth: % and year-on-year.

On the other hand, energy projections are customarily coupled with WGDP projections made independently. However, it stands to reason that both should be somehow related. Besides, the stabilization hypothesis is frequently grounded on the assumption that once income per capita reaches a sufficiently high level, births per couple decrease, sometimes even falling beyond the reproductive value—i.e., slightly below 2. To test this hypothesis, a simple model for population has been estimated as follows:

$$log(Pop_t) = 0.804 \times log(GDP_t) - 0.632 \times log(Pop_{t-1}/GDP_{t-1}) + (consts.) \tag{A14}$$

where Pop_t, GDP_t are respectively (world) population and GDP in year t, $(consts.)$ includes the constant, three dummies for outlying observations and the equation error, the estimation period spanning the years 1900 to 2017—annual observations. The fit of the equation is very high—$R^2 = 0.999$—all coefficients are highly significant statistically, and there are no further statistical issues worth mentioning—$DW = 1.64$, the null hypothesis of

Gaussian errors accepted. The equation has been estimated accounting for different variances before and after 1947, and by means of a robust procedure correcting for unspecified heteroskedasticity and autocorrelated errors. As for stability, and although the individual coefficients do change in a shortened and more recent sample covering the years 1947–2017, the stability of the long-run dynamic equilibrium coefficients is remarkable. The fit is portrayed in Figure A2, where it can also be seen that it is, indeed, quite tight, and where the higher variance in the period ending in 1950 can also be observed—accounted for in the estimation procedure. Finally, the series for WGDP has been estimated combining WB data after 1960, and historical data reported by the leading source in this field; A Madison, see [132].

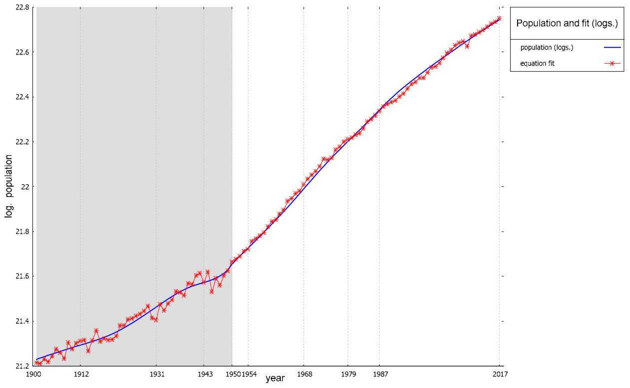

Figure A2. Fit of model B1.

The estimation results do show a negative impact of income per head on population growth with an elasticity of −0.632, but also show a current and positive elasticity for GDP of 0.834: the resulting total elasticity of population with respect to GDP in the long-run dynamic equilibrium turns out to be positive and smaller than one, yet significantly greater than zero, implying that historically, along almost 120 years, a 1% GDP increase has implied, on average, a 0.468% population increase—smaller than one, and lower than the immediate impact of 0.804, yet significantly greater than zero.

Appendix B.2. Dynamic Equilibrium

Simulations are frequently conducted based on simplified assumptions, and notably, almost always omit the implied randomness derived from the estimation procedures. This overlooks uncertainty and may lead to a heavy underassessment of the risks involved—see, e.g., [122,141], for a more thorough discussion. To address both issues, it is first convenient to solve the estimated dynamic model of (B1) for a long run growth equilibrium, under the assumption of constant growth for the explanatory driving variable, GDP in this case. To do so, the model can be, first, conveniently framed in a simplified way as follows,

$$y_t = c + a \times y_{t-1} + b \times x_t \tag{A15}$$

If the driving variable of the model, x_t, grows at a constant rate, $\overline{\Delta x}$, and ($|a| < 1$), it can be shown after some otherwise straightforward algebra that the long-run dynamic equilibrium of the model when y_t will also grow at a constant rate $\overline{\Delta y}$, is given by,

$$y_t = \left(\frac{b}{1-a}\right) \times x_t + \frac{c}{1-a} + \left(\frac{b \times \overline{\overline{\Delta x}} - \overline{\Delta y}}{1-a}\right) \tag{A16}$$

Taking first-order differences of this equation, the $\overline{\Delta y}$ equilibrium growth rate can be written as a function of the driving growth rate $\overline{\Delta x}$, i.e.,

$$\Delta y_t = \overline{\Delta y} = \left(\frac{b}{1-a}\right) \times \overline{\Delta x} \tag{A17}$$

given that the last two terms in (A16) are constant, and, therefore, become nil after differentiation. Replacing now (A17) in (A16) and operating, the final long-run equilibrium solution as a function of the equilibrium growth rate of the driving variable is immediately given as,

$$y_t = \mu \times x_t + \delta + \gamma \times \overline{\Delta x} \tag{A18}$$

where $\mu = b/(1-a)$, $\delta = c/(1-a)$, and $\gamma = -a\mu/(1-a)$. For the specific estimated model reported in (B1), the values are, $\mu = 0.468$, $\delta = 14.33$, $\gamma = -0.802$. The variances and covariances of these coefficients can also be derived from the corresponding values for the initial parameters in the model (B1); see, e.g., [153].

Appendix B.3. Randomness and Risk

The methodology to analyze projections and their potential risks, once randomness is acknowledged and accounted for, was presented first for the energy field in [14]. It can be similarly applied to population projections analysis, as discussed next. First, the probability that population increases above a given value or conversely is of interest, as reported in lines 2 to 4 in Table A1, i.e.,

$$Prob(Pop_{2050} > 17.2) = 20\% \tag{A19}$$

under simulation I; see Table A1. A related measure of concern is the average expected population, if it increases beyond that value, i.e.,

$$E(Pop_{2050} \big| Pop_{2050} > 17.2) = 22.3 \tag{A20}$$

under simulation I; see Table A1, denoted '*mean* 20%', and similarly for remaining probabilities.

Appendix B.4. Simulation Results

Simulating the model requires, as a minimum, a simulation model for GDP. This can be done in an ad hoc fashion assuming arbitrary constant growth rates, as is usually done in most scenarios, or else setting up a more specific model based on statistical analysis. In the present case, a middle-of-the-way solution has been implemented, detailed next. First, a nonparametric fit of the density for the historical data yields substantial skewness, −2.2, and excess kurtosis, 7.89, implying thereby departures from Gaussianity; then, the simulation has been conducted under the normality assumption but taking as the mean the empirical median, slightly higher because of the left-skewness, and for the standard deviation, the observed interquartile range, slightly lower.

Considering now a no-random solution implying, therefore, constant parameters, a zero-equation error, and a constant GDP growth rate, the solution reported in (A16) yields a value of 12.4 billion, somewhat higher than current UN projections, although fairly close and approximately 60% above current values in 2020; see [132]. A risk analysis, nevertheless, yields a far less reassuring picture as reported next in Table A1.

Table A1. 2050 World Population Projections.

	2050 World Population Projections (Billions)		
	I	**II**	**III**
mean	13.4	12.6	13.2
ProB (20%)	17.2	14.3	16.8
ProB (10%)	20.6	15.4	19.6
ProB (5%)	23.9	16.3	22.4
mean 20%	22.3	15.7	20.8
mean 10%	25.3	16.5	23.8
mean 5%	28.3	17.8	26.1

Notes: (I) overall random solution (parameters and x_t growth rate). (II) random parameters solution (x_t growth rate set at its average constant value). (III) random x_t growth rate solution (parameters constant at their expected value).

In the worst-case scenario, e.g., reported on the last line, column I, Table A1, there is a 5% chance that the world population goes beyond 23.9 billion—line 4—in which case, its expected value would be almost 30 billion (28.3), i.e., nearly three times the standard conservative projections that give a value close to 11 B.

Appendix B.5. Discussion

The first result to be remarked is that population and GDP projections cannot be made independently, and the least that should be done is a combined projection coherent with a model that relates both magnitudes. The second is that, although it is true that income per capita increases dampened population growth, the final impact of GDP on population although lower than one, is also significantly higher than zero implying that, according to 120 years of historical data, population growth cannot be decoupled from GDP growth. The third and last is that the randomness of estimated values for the parameters of the model result in sizeable projections of uncertainty and, therefore, significant risk.

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