

Article

Physical Constraints on Global Social-Ecological Energy System

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Abstract: Energy is the main driver of human Social-Ecological System (SES) dynamics. Collective energy properties of human SES can be described applying the principles of statistical mechanics: (i) energy consumption repartition; (ii) efficiency; (iii) performance, as efficient power, in relation to the least-action principle. International Energy Agency data are analyzed through the lens of such principles. Declining physical efficiency and growth of power losses emerge from our analysis. Losses mainly depend on intermediate system outputs and non-energy final output. Energy performance at Country level also depends on efficient power consumption. Better and worse performing Countries are identified accordingly. Five policy-relevant areas are identified in relation to the physical principles introduced in this paper: Improve efficiency; Decouple economic growth from environmental degradation; Focus on high value added and labor-intensive sectors; Rationalize inefficient fossil fuel subsidies that encourage wasteful consumption; Upgrade the technological capabilities. Coherently with our findings, policies should support the following actions: (1) redefine sectoral energy distribution shares; (2) Improve Country-level performance, if needed; (3) Reduce intermediate outputs and non-energy final output; (4) Reduce resources supply to improve eco-efficiency together with system performance.

Keywords: energy statistics; social-ecological system; thermodynamics; efficient power; energy performance



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1. Introduction

Energy availability, which is extracted and processed from the environment, is basic for life, as well as for civilization [1,2]. Specific energy constraints exist, affecting species richness and evolution, as well as human evolution [3]. Human evolution—biologically and socially—critically depends on energy and available environmental resources, which, in turn, are related to a continuous and mutual interaction between man and the environment. The existence of this interaction led scholars to define the concept of Social-Ecological System (SES hereafter), focused on the needed integration between the humans and the environment, considering both the biophysical and social dimensions of our lives [4,5].

According to the official data delivered by the International Energy Agency (IEA), total primary energy supply (TPES hereafter), in 2019, reached 606 PJ. This growth is likely to continue in the future to respond to the existing social, economic and resource demand and challenges [6]. Such a demand for energy displayed a rapid growth since the beginning of the 'Great Acceleration', about 70 years ago [7–9], when population, GDP and production on our planet started to increase in an unprecedented way. The generated impacts are increasing as well, together with the risk of crossing the tipping points (i.e., planetary boundaries), which constitute the boundaries of a safe space for humanity [10,11].

Thus, the future of civilization will depend on how humans will shape their production and consumption systems [12].

Within this context, the words ‘transition’ and ‘transformation’, respectively indicating the physical manifestation related to a change and the process of large socio-technical systems change, need to be better understood [13]. In this respect, energy policies play a relevant role in facing various problems: the high emission levels coming from high energy consumption [14]; The need to support economic development by sufficient energy availability, which is incompatible with the previous point [15]; The existing fragmentation of energy and environmental policies, which lack of appropriate integration [16]; The need to reconsider an energy justice framework [17]. These policies should rely on a clear understanding of energy system properties, in order to guarantee both the permanence of a safe space for humanity and the preservation of the biosphere and the environment, whose quality have been deteriorated by human activities. Such a purpose constitutes the basis of ecological civilization as a possible approach to policy-making. As a form of human civilization, ecological civilization is based on respect and protection of nature, taking the harmonious symbiosis among humans and nature as a pivotal purpose, establishing sustainable production and consumption patterns and focusing on guiding people to get on a sustainable and harmonious development path. As awareness grows about the impacts on ecological systems, the transition toward an ecological civilization needs more sustainable ways of producing and distributing energy, in order to preserve a safe space for humanity.

This paper addresses global and national energy data, interpreting them through the lens of physics, applied to the analysis of social-ecological systems. Thus, this work is also intended as a contribution to the sub-domain of physics, named ecophysics, which aims to apply different physical methods to ecology [18,19]. In particular, the paper aims at answering to the following basic questions: What are the most relevant energy constraints, as known from physics, influencing the features of human SES at global scale? How and to what extent they impact on ecological civilization? Policy and research implications are then derived.

2. Materials and Methods

A homeomorphism exists between ecological systems and statistical mechanics [20]. Consequently, human SES energy-related properties can be interpreted also on the basis of statistical mechanics. A human SES, such as a society embedded in its environment, is a multi-level open structure, whose components evolve, passing through different microstates within a higher-scale macrostate. The option of measuring each microstate as a separate subsystem depends on its statistical independency. This is not an intuitive fact, since SES are open systems. Nonetheless, being microstates both macroscopic and smaller than the whole system, they can be treated as independent for sufficiently small time intervals [21]. The statistical independency of microstates guarantees the validity of Liouville theorem. As a consequence, the basic properties of each microstate can be expressed, as first integrals, as functions of energy. This is true for sufficiently short time intervals, as written before. During periods, in which the boundary conditions are stable, traditional criteria from irreversible thermodynamic theory are then sufficient for a quantitative prediction of ecosystem responses to a perturbation [22]. Otherwise, non-equilibrium thermodynamics theory should be applied to measure the existing resources flows, as done in environmental accounting.

The thermodynamic state of a non-isolated system can be described in energy terms using Gibbs free energy G [23]. Its explicit-form equation is:

$$G = E + pV + \mu N - TS \quad (1)$$

In particular, the term E represents the internal energy, which is a ‘structural’ variable, used to quantify the energy invested in keeping together a structure composed by N elements. The product of p and V measures the (mechanical/external) work performed.

The product between μ and N assesses the accumulation of energy by the N components of the microstate, on the basis of individual energy attribution, measured through the variable μ (chemical potential). Finally, the last term, where both entropy S and temperature T are present, weights the loss of the subsystem related to dissipation phenomena. Equation (1) can be addressed in a simple way. From one side, the left-hand term represents the availability, in the form of available power, which can be extracted from the environmental resources, constituting a reservoir that is necessary for the survival of a population of organisms [1]. This reservoir supports the biological needs, differing for each living specie, which are quantified on the basis of a characteristic basal power, defined by the basal metabolic rate, measured in units of W/kg . Together with the basal power, it is possible to define an external power, or performance, being the equivalent of mechanical work in classical thermodynamics, which can be intermittent [24]. The development of technologies, which constitute the technosphere, allowed humans to have also an additive power. This is why it is possible to consider also a Socio-Technical system. For sake of simplicity, however, we will preserve the original nomenclature, considering a Social-Ecological system as the object of our analysis. What constitutes the basal power for an individual, that is equivalent to the product μN in Equation (1), is paralleled by the individual consumption of energy for the N components of the system, that, in our case, is constituted by the number of human beings, N . Humans, as any 'social' living specie, display an internal interaction. The interaction of components is supported by a certain amount of energy consumption, equivalent to E , in the thermodynamical expression given by Equation (1). The external performance is paralleled by pV in thermodynamics. Finally, in parallel to the consumption or accumulation of energy within the system, a certain amount of power is dissipated, while the balance is maintained by a change in performed work [25].

A simplified representation of societal energy resources metabolism is provided in Figure 1. In particular, the components of energy supply and consumption, that will be analyzed and discussed in this work, are considered as parallels of the thermodynamic expression of Equation (1). This graphical representation combines the energy supply (as Total Primary Energy Supply), extracted from the environmental reservoirs by humans, as input of the system. The energy input, that constitute the available energy to support the societal metabolism, contributes to the internal system dynamics, which is constituted by different factors, according the right hand-side of Equation (1). In particular, the internal system dynamics is supported by energy own use, share of energy resources (imports and exports) and a partial transformation of fuels into non-energy products. System internal energy use (E) is represented by the energy resources supporting the connectivity within the system, such as in the case of energy use for transportation or the Information and Communication Technologies (ICT) sector. There is, then, a fraction of energy that is used for supporting the activities of individuals (or small groups of individuals), such as in the case of households' energy consumption. This is represented by its thermodynamic equivalent, that is the potential (μN). These two factors were used according to the services subdivision given by the literature [26]. Applying a holistic perspective, the system has an external performance, which parallels the definition of works (pV) in thermodynamics, that is constituted by industry, agriculture and fisheries categories, identified in the IEA official statistics. Power losses are, finally, accounted, that parallel the factor TS in Equation (1). This representation is coherent with IEA official statistics subdivision and IEA available Sankey diagrams, from which data can be easily extracted.

In the framework of global energy systems, a quantitative role can be also played by that part of the throughput energy which is stored somewhere along the input-output path. This aspect has been relevant for example in the prize fluctuation of oil during global political crises, and it is now becoming even more relevant due to the need of compensating renewable sources that are not constantly available, like in the case of solar and wind power plants. From a systemic point of view, the presence of stored quantities of energy correspond to the formation of stocks that de-couple inflows and outflows [27], allowing the system to adapt time to time to external driving forces fluctuations. On the

other hand, the presence of storage sectors does not affect the description of the overall dynamics of the energy flow, especially if the described system has a global nature not only in terms of space boundary, but also in terms of time scale. Indeed, when a system is operated under stationary conditions the presence of storage stocks is irrelevant for its dynamic description. We expect that in a world where energy supply relies mostly in renewable-possibly intermittent-sources, the relationship between offer and demand will be somewhat reversed, with the former determining the latter. However, the presence of storage points should not alter significantly the dynamic regimes and the efficiencies of the global energy systems, acting possibly as factors able to increase the system resilience.

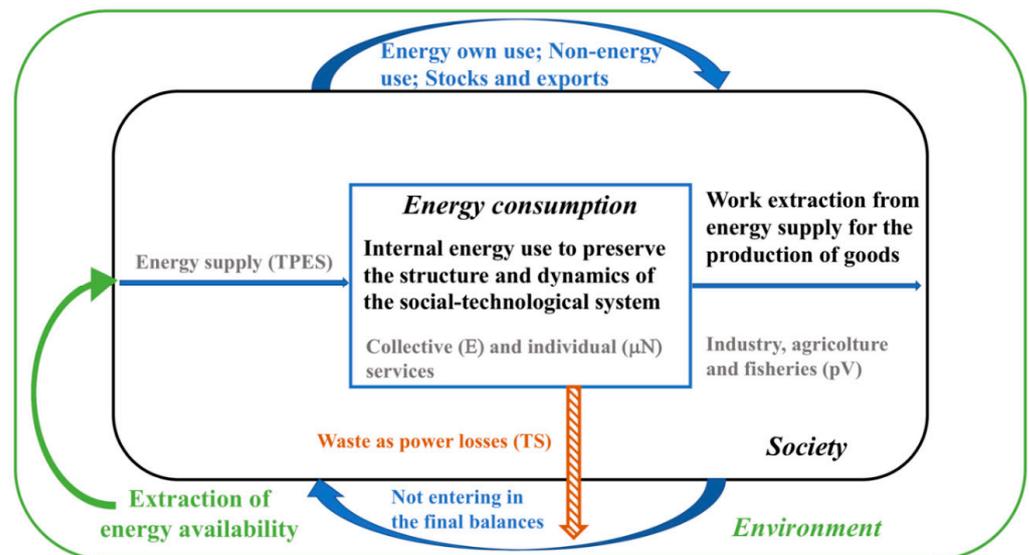


Figure 1. Basic simplified representation of societal energy metabolism and its components. Energy availability, embedded in energy sources, is extracted from the environment, becoming available to humans as energy supply (TPES). Energy is processed within society, considering also the use of technologies, to maintain its structure and functions, while some of it is used to support the production of different goods. Finally, part of the energy is dissipated in the environment, while a part of TPES re-circulates within the system without being consumed along metabolic processes.

Considering biological evolution, since many organisms live only in a comparatively narrow range of temperatures (T) and pressures (p), T and p can be treated as constants [28], and the equilibrium state corresponds to a minimum of Gibbs free energy [29]:

$$\Delta G \leq 0 \quad (2)$$

Therefore, energy constraints in relation to SES evolution can be modelled as quasi-equilibrium states in complex subsystems [30,31] or “asymptotic stationary states of imbalance” [32,33]. The validity of year-based energy statistics at Country level, which will be discussed in the following, is based on such physical roots.

Human SES energy features depend on Gibbs free energy. In particular, a coherent description of SES should be take into account various aspects [34]: (1) the existence of evolutionary potentials as analogues of chemical potentials, defined as specific components of the Gibbs free energy related to the unit of mass; (2) the increase of energy density in the volume V of any evolving biological subsystem, linked to the increased potential; (3) the increase of stable higher-hierarchy levels, that depend on their energy capacity, which grows at higher steps of the hierarchy; (4) the energy cost of formation or self-assembly of the highest hierarchical levels as paid by lower levels, whose structures are incorporated into the next higher level. This is known as principle of substance stability [35], also valid for free energy [36].

The evidence of a hierarchical network of energy transformation processes, which joins different system scales, emerged as a fundamental concept in the studies by H.T. Odum [37,38]. Energy, that is the cumulative contribution of available energy to components and processes within an ecosystem, was used to identify and explain hierarchical structures and their self-organization. In particular, complex systems tend to organize their own structures and populations such to maximize their contribution to the empower (i.e., the time rate use of available energy) of the surrounding system, a concept encompassed it the so-called maximum empower principle [39]. Law of substance stability and empower maximization are strictly linked to the least-action principle in its thermodynamic form [40]. Action, as the product of energy variation within a given time interval, is minimized along a system transformation, and this minimization was indicated to occur by increasing the empower of the system [41]. SES optimization strategies, during which SES hierarchy, structures and functions rearrange, depend on this principle [42–44] and time stability of structures also increases in association to higher hierarchical SES levels.

The quantification of efficiency is relevant in analyzing the performance of a system. However, efficiency is not the best performance descriptor for a SES. In fact, as explained also by Odum and Odum [27], “in the self-organizational processes, systems develop those parts, processes and relationships that capture the most energy and use it with the best efficiency possible without reducing power”. The same statement is rephrased in the same work as: “in the self-organizational processes, systems develop those parts, processes and relationships that maximize useful empower”, that is the current formulation of Odum’s maximum empower principle. It was proved that the same principle can be quantified through a parameter, called efficient power [45,46], defined as:

$$P = \eta W_{\text{out}} \quad (3)$$

where P is the efficient power, W_{out} is the power output (i.e., power consumption, in our case) and η is an efficiency indicator, as the ratio between the system power output and its power input. It is worth remarking that this indicator is parallel and not alternative to the key indicator of efficiency, as defined in classical equilibrium thermodynamics, calculated as the ratio of net work and heat input. The unified validity of Equation (3) was proved in the literature [47,48]. The choice of this efficiency indicator derives from its standard use in the study of thermodynamics of heterogeneous solutions, later evolved in the study of physical principles regulating the dynamics of ecosystems [19]. This parameter is currently used in the context of research on fundamental constraints ruling the self-organization of complex systems, can be applied to different systems, including human societies, as proved by H. T. Odum works [49].

The equations, summarized in Table 1, as well as efficiency calculation, are applied to data from International Energy Agency (IEA hereafter) to derive some indications, potentially meaningful for energy policies.

Table 1. Equations applied to analyzed IEA datasets, and their purpose of application. Please, note that the chosen efficiency indicator parallels, not being alternative to, the key indicator of efficiency, as defined in classical equilibrium thermodynamics, calculated as the ratio of net work and heat input.

	Analysed Data	Application
$G = E + pV + \mu N - TS$	World energy statistics time series derived from Sankey diagrams	Sectoral partition (as share %) of energy consumption and losses
$\eta = \frac{\text{Final power consumption [TW]}}{\text{Total primary power supply [TW]}}$	<ul style="list-style-type: none"> Global energy system (physical) efficiency trend Country-level energy statistics, as a factor within efficient power 	Energy efficiency global trend Efficient power
$P = \eta W_{\text{out}}$	Country-level energy statistics, limited to those Countries for which validated new time series are available	Country energy performance comparing efficient power (P) with power supply (derived from Total Primary Energy Supply)

3. Results

Global power appropriation grew up through the millennia. Data on global power supply from primary resources are summarized in Table 2. This represents the availability, used to power up our civilization.

Table 2. Global power (expressed in Watts) for different epochs or years (Data extracted from [50]; ^(a) is derived from IEA official statistics, available from IEA website).

Epoch or Year	Power Consumption [W]
Pre-agricultural epoch	3.17×10^2
1750	3.17×10^{11}
1850	6.34×10^{11}
1900	1.43×10^{12}
1950	3.17×10^{12}
2000	9.33×10^{12}
2019 ^(a)	1.92×10^{13}

In 29 years, from 1990 to 2019, energy total production on year base increased from 11.7 TW to 18.9 TW. This amount represents also the extracted energy, available, as additional power, to support the dynamics of the global system composed by humans and the technosphere (i.e., the ensemble of human technologies). On the other hand, final consumption increased from 8.3 TW to 13.2 TW. These data are publicly available from the statistics section of IEA. The temporal trends of global energy production and consumption (both expressed in terawatts) are shown in Figure 2.

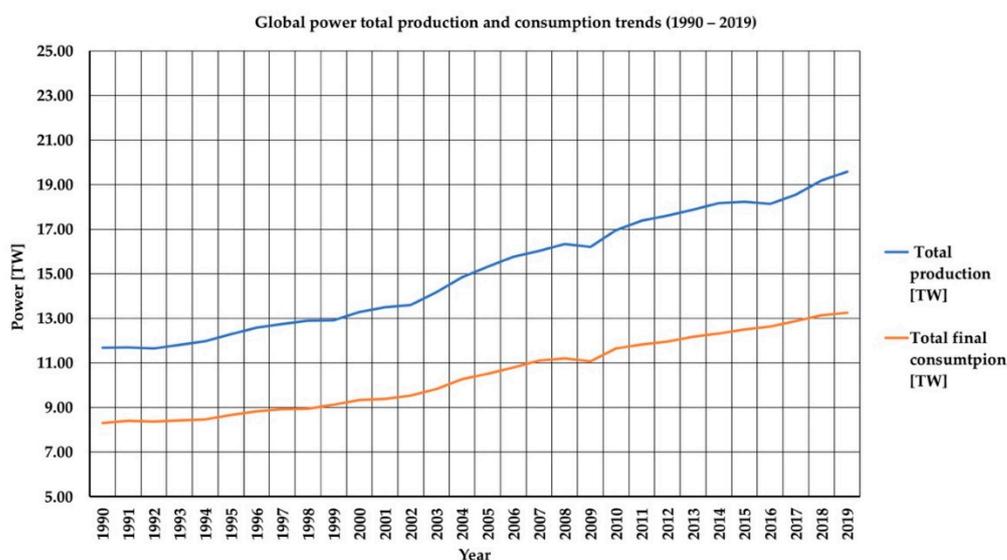


Figure 2. Total global power production and consumption, expressed in terawatts, from year 1990 to year 2019. International Energy Agency Data (data available from: [51]).

Global system power losses, on the other hand, also increased from 2.1 TW (year 1990) to 3.8 TW (year 2019). Complete data of production, final consumption, efficiency and system losses, referred to the same time interval, are detailed as Supplementary Material (Table S1). Looking at Country-level data, it is possible to review energy production and final consumption values, defining the 10-top energy-producing and energy-consuming Countries. Their ranking, from highest to lower values of production and consumption, giving also the associated values in Million tons of oil equivalent (Mtoe), is reported in Tables 3 and 4. Data refer to year 2016. It is important to underline that final consumption data, exposed in Table 4, were elaborated to exclude imports, exports, energy own-use, non-energy use and losses.

Table 3. Top-10 energy-producing countries (highest to lowest). Data of energy production are expressed in Million tons of oil equivalent (Mtoe). Data are referred to year 2016.

Ranking	Country	Energy Production from Primary Sources [Mtoe]
1	China	2538
2	United States	1952
3	Russia	1346
4	Saudi Arabia	685
5	India	586
6	Canada	471
7	Indonesia	437
8	Australia	384
9	Iran	355
10	Brazil	287

Table 4. Top-10 energy-consuming Countries (highest to lowest). Data of energy final consumption, excluding imports, exports, energy own-use, non-energy use and losses, are expressed in Million tons of oil equivalent (Mtoe). Data are referred to year 2016.

Ranking	Country	Energy Final Consumption [Mtoe]
1	China	3123
2	United States	2204
3	India	884
4	Russia	692
5	Japan	437
6	Germany	311
7	Brazil	289
8	South Korea	288
9	Canada	273
10	Iran	248

The difference between energy production and consumption at Country-level supports the definition of two further rankings: the top-10 Countries with an energy production surplus (Table 5); the top-10 Countries with an energy production deficit (Table 6). Inputs for both of the tables are given by IEA. Given values refer to year 2016. The global energy system physical efficiency, being different from the economic efficiency (called energy intensity) used as indicator by IEA, is measured as the ratio between final consumption and primary production (i.e., Total Primary Energy Supply) at world level. Its trend is displayed in Figure 3.

Table 5. Top-10 Countries (highest to lowest Mtoe values) for energy production surplus, obtained by the difference between energy production and consumption. Latest available data, expressed in Mtoe, refer to year 2016.

Ranking	Country	Energy Production Surplus [Mtoe]
1	Russia	654
2	Saudi Arabia	462
3	Australia	267
4	Indonesia	219
5	Canada	198
6	Norway	179
7	Kuwait	144
8	United Arab Emirates	139
9	Nigeria	112
10	Venezuela	109

Table 6. Top-10 Countries (highest to lowest Mtoe values) for energy production deficit, obtained by the difference between energy production and consumption. Latest available data, expressed in Mtoe, refer to year 2016.

Ranking	Country	Energy Production Deficit [Mtoe]
1	China	−585
2	Japan	−399
3	India	−298
4	United States	−252
5	South Korea	−225
6	Germany	−193
7	Italy	−118
8	France	−114
9	Turkey	−101
10	Taiwan	−99

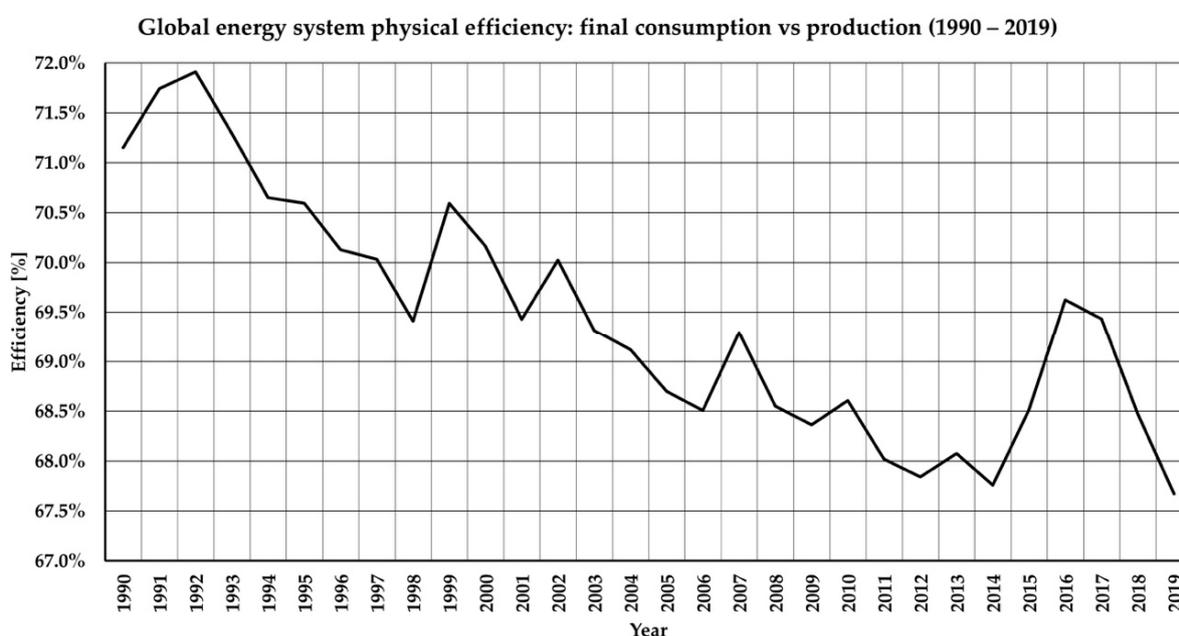


Figure 3. Global energy physical efficiency variability, as percentage value, from year 1990 to year 2019. Data source: International Energy Agency (data available from: [51]).

Final consumption, as shown in IEA Sankey diagrams, also includes a fraction named ‘non-energy use’, defined by IEA as the fraction of final consumption covering “those fuels that are used as raw materials in the different sectors and are not consumed as a fuel or transformed into another fuel”. This fraction, entering into flows of materials, is removed from final consumption before calculating the efficiency since it does not pertain directly to energy flows. Physical efficiency declined from 71% (year 1990) to 67% (year 2019). Results mainly depend on the higher rate of TPES increase with respect to consumption rate growth. However, this result also depends on the global power losses trend, which is represented in Figure 4 for the same years period.

A separate accounting, at Country level, for physical efficiency should not be considered. In fact, due to the existing imports and exports among nations, energy statistics at national level cannot be treated as independent statistical microstates within the global energy system. Instead, by applying Equation (3), it is possible to put together the overall structure of national efficient power consumptions, taking IEA statistics as database. In this case, Countries are treated as components of a bigger system. In particular, their energy properties are considered as a set of microstates within a global macrostate. Using the data referred to 41 Countries for the years 2000, 2005, 2010 and 2015, the relation between power

supply (derived from TPES) and P (derived from Equation (3)) is shown. In particular, efficient power consumption comes to be a linear function of power supply ($R^2 = 0.99$), whose coefficients are variable for each year, as shown in Figure 5.

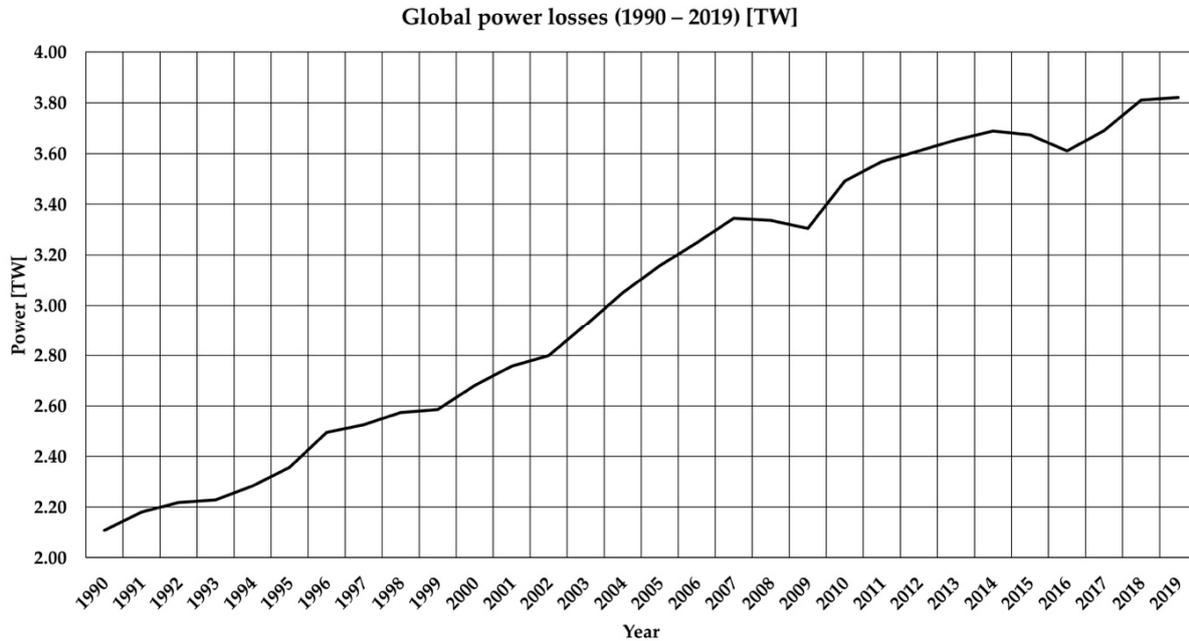


Figure 4. Global power losses, expressed in terawatts, from year 1990 to year 2019. Data source: International Energy Agency (data available from: [51]).

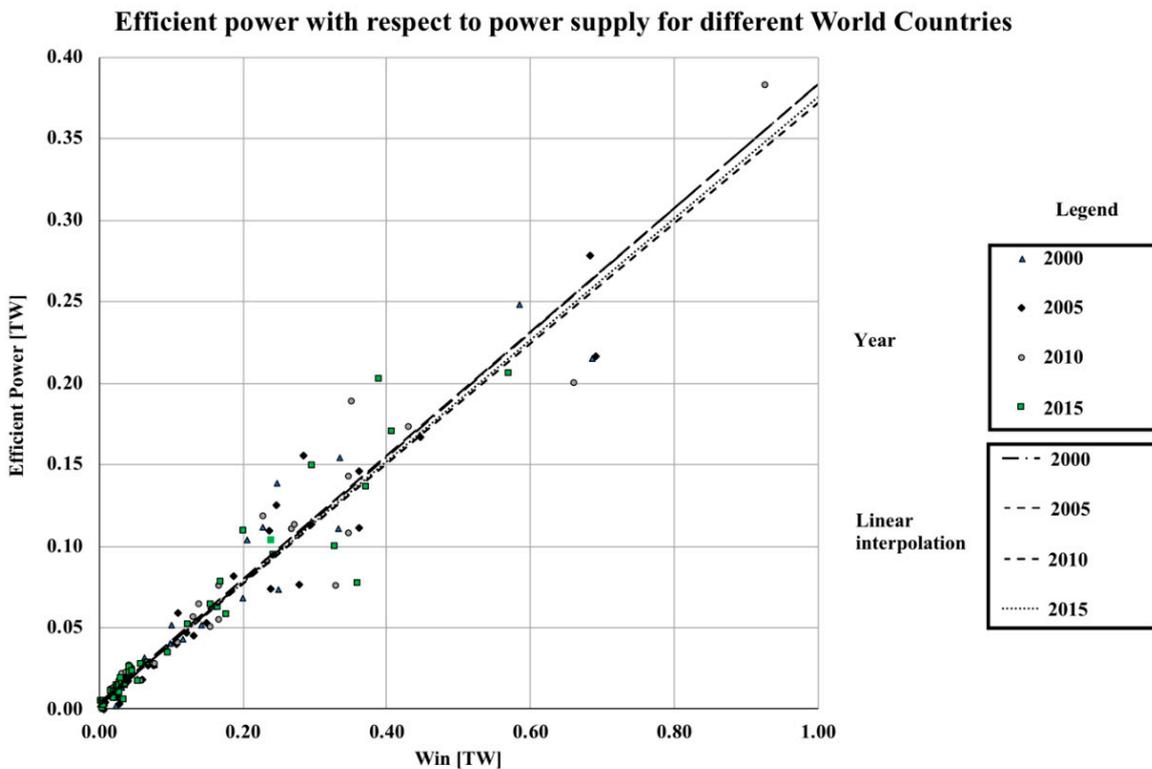


Figure 5. Efficient power consumption, in terawatt, with respect to input power, in terawatt, at Country level. Data source: IEA. Data refer to years 2000, 2005, 2010 and 2015. Each point represent a Country. The year tendency line indicates the existence of a linear relation between power input and efficient power consumption, with a high level of correlation between the two variables ($R^2 = 0.99$). Note that year 2000 and year 2005 tendency lines are almost superimposed.

According to the maximum empower principle, global energy system components rearrange towards an optimal performance. This performance can be quantified through the use of efficient power (Equation (3)). In particular, each Country rearranges its efficient power consumption in proportion to its power supply. In this way, the overall energy system maintains a regular structure, whose existence is also proved by the linearity between power supply and efficient power consumption. Thus, a growth of efficient power consumption proportioned to the growth of power supply would represent an optimal condition for each Country. Data for Figure 4 are available in Table S2 as Supplementary Material. With respect to year 2015, Countries with better performance included Austria, Turkey, United Kingdom, Italy, Indonesia, Canada, Germany, India and United States. On the other hand, Countries with worse performance include Estonia, Iceland, Latvia, Slovenia, Luxembourg, Singapore, Norway, The Netherlands, South Korea, Japan and People's Republic of China.

It is worth stressing that a better energy performance does not imply also an eco-efficiency. In fact, eco-efficiency depends on a holistic assessment of resources use, that should be regulated by resource-saving policies. Considering years 2000, 2005, 2010 and 2015, Turkey, Indonesia and Italy maintained a better performance with respect to the reference linear trend. Instead, Slovenia, Singapore, Australia, Korea, France and Japan had a worse performance. It is noticeable that, due to efficiency improvements, United States exhibited a better performance in the last two years considered, whereas China data show an opposite behavior. This might

Depend on the efforts to increase internal energy stocks, as well as on the poor energy efficiency of several economic sectors. Economic efficiency (usually called 'energy intensity' by IEA) is improving. In particular, the unitary cost of energy in USD is declining, as shown in Figure 6. Data based on the period between 1990 and 2011 use global GDP values available from Earth Policy Institute [52], and are available as Supplementary Material.

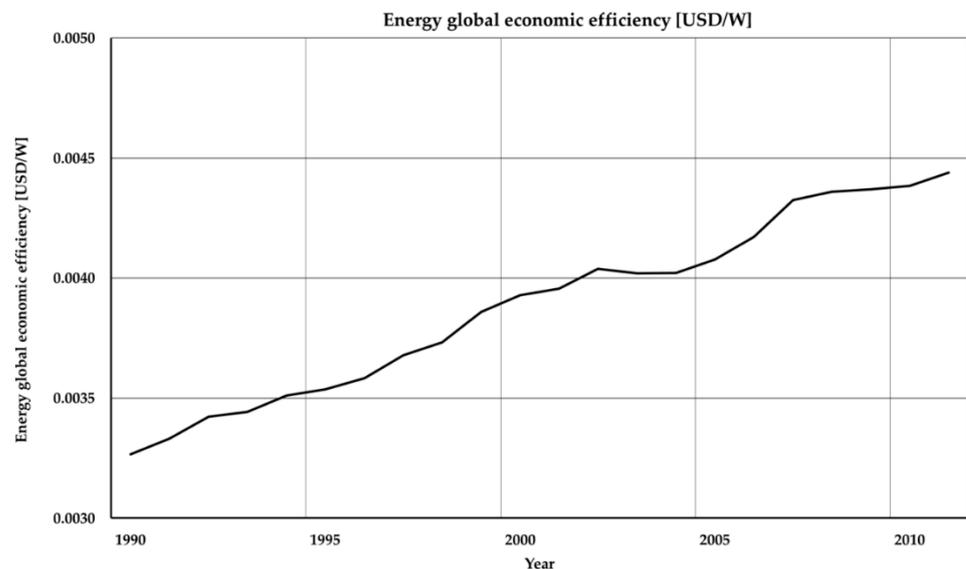


Figure 6. Energy economic efficiency, defined as energy intensity (as defined by IEA: TPES divided by the GDP) as ratio of W/USD from year 1990 to year 2011. Power data derive from IEA, while GDP data (actualized to year 2011) are available from Earth Policy Institute online database [52].

4. Discussion

4.1. Physical Framework Supporting Data Interpretation

Comparing Figures 3 and 6, it is possible to see that, from one side, the global physical efficiency, depending on extraction from primary sources, final consumption, with the exclusion of imports, exports, power losses, non-energy use and energy-own use, power losses, is declining. On the other side, the unitary cost, in USD, of energy, is declining,

showing that the economic cost of the system is becoming cheaper. Historically, energy needs increase, as global economies develop and become more complex [53]. While energy system components grow together with its complexity, supported by lower costs, the physical efficiency, driven by power losses, is also increasing. This tendency is also stimulated by the growing weight of virtual financial operations. However, financial trading doesn't compensate the state and communities with respect to external resources depletion and external environmental damage or loss of livelihood. Meanwhile, some global currency policies, such as 'quantitative easing', could lead to a further growth in energy use.

Looking at efficiency data from different perspectives (i.e., physical and economic ones) might lead to different system interpretations and policy options. Considering the decline of global system physical efficiency, the positive statement [54], affirming that "Global energy savings from efficiency improvements since 2000 led to a reduction in greenhouse gases (GHG) emissions of just over 4 billion tonnes of carbon dioxide equivalent (Gt CO₂-eq) in 2016" might become weak or, at least, too simplistic. The driver of such a tendency is the growth in materials processing, which leads to higher use of energy and to higher GHG emissions [55]. These savings, ultimately conceived in economic terms, avoid to include the existence of growing power losses. Instead, economic efficiency and environmental considerations should not be disentangled in the future. In fact, a study proved the existence of a long-term positive correlation between physical efficiency and environmental performance, considering the energy use of 129 world Countries [56]. Thus, a decline in overall energy system physical efficiency implies a decline in environmental performance, making the above positive statement too optimistic.

Actions are required to counterbalance this trend. In this respect, considering 13 world regions and coupling materials and energy use with carbon emissions, a research showed that OECD economies, as well as developing economies, could significantly reduce their materials use and emissions with little negative impacts on their economic growth [57]. This process should be supported by a wider use of several technologies to extract renewable energy from organic matter, to substitute fossil with renewable fuel and to optimize hybrid energy networks [58].

The metabolism of energy resources, in terms of material flows analyzed under a physical perspective, constitutes a constraint to the evolving complexity of social-ecological systems [59]. In fact, the evolution of societal complexity depends critically on energy availability [60,61]. In particular, SES complexification leads to higher energy costs and dispersion, which is used by SES to maintain the existing thermodynamic disequilibrium and structure [62]. This co-evolutionary pattern is indirectly confirmed by trends reported in Figures 2, 4 and 5.

World sectoral final consumption, power losses and remaining differences (i.e., energy own-use, exports, non-energy use and stocks) can be grouped, according to the given representation. Figure 7 details such a partition on yearly base at a global scale, expressing the numbers as percentage of TPES. Available data cover the period from 1973 to 2019. Original data are reported as Supplementary Material.

It is, then, addressed that: (1) energy use for industry, agriculture and fisheries, as percentage of TPES, declined, until year 2014, when the total energy use for these sectors increased; (2) residential sector energy use, corresponding to individual energy appropriation, is also declining; (3) energy consumption for common services is almost stable, besides the decline displayed in the last three years analyzed; (4) power plant losses grew until 2007, then displaying a little decline; (5) differences associated to energy industry own use, stocks, exports and non-energy use are growing.

Even if traditional energy-intensive industries still play a key role in energy consumption, other factors are becoming important. The first one is the growth of real power losses along societal energy metabolism processes. This loss, as shown before, mainly depends on the complexification of socio-economical system. The second is related to a small increase of exports (this factor depends on global markets), stocks (depending on energy security

issues) and development of non-energy final products, derived from accounted energy sources. This difficulty in performing a correct account of material flows depends on the fact that intermediate products of complex supply chains are often depending on activities labeled under different and apparently uncorrelated economic sectors in Input-Output tables [63].

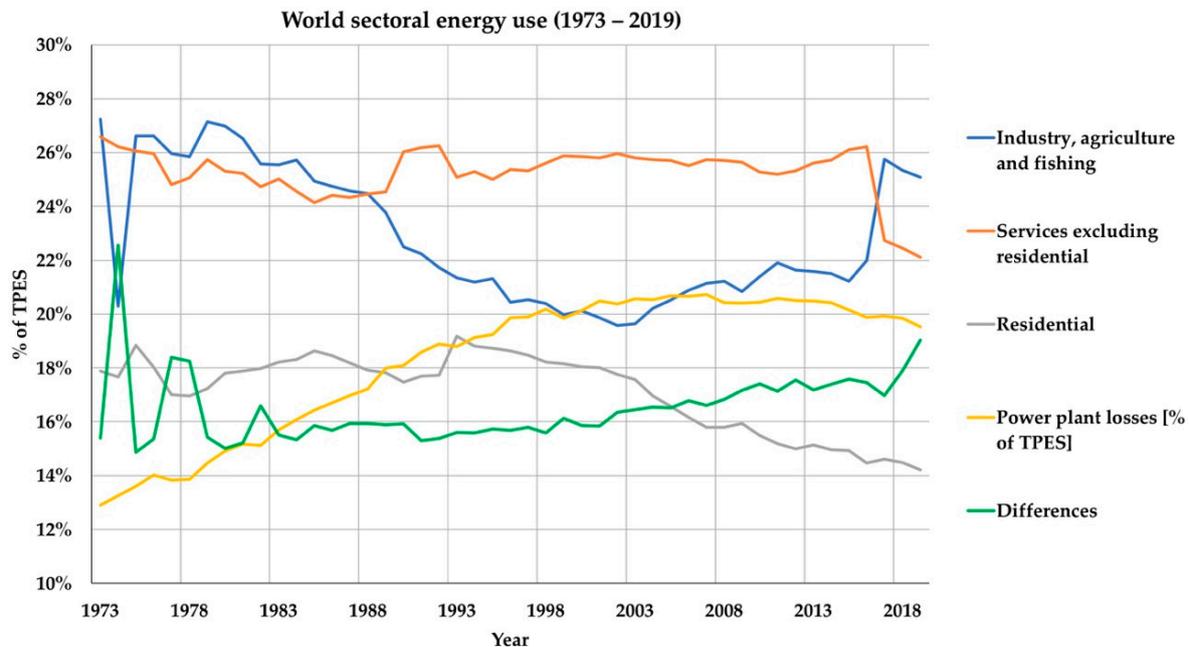


Figure 7. World sectoral final consumption, power losses and remaining differences (i.e., energy own-use, exports, non-energy use and stocks) interpreted according to Figure 6. Data include the years from 1973 to 2019. Data, expressed as percentage of input (i.e., Total Primary Energy Supply), are provided from official IEA statistics.

4.2. Risks Connected to the Evolutionary Dynamics of Global Energy Metabolism

Existing risks for the future of human SES must be assessed, in order to implement appropriate policies. Global power appropriation grew up together with ecological civilization. The costs of such appropriation of environmental resources are increasing, together with energy production. The depletion of non-renewable resources is the first factor of risk. In fact, energy withdrawal from ecosystems—in particular, the one due to biomass harvest—cause a loss of biodiversity [64]. Biodiversity protection is of major importance for several reasons: (1) its influence on the efficiency, by which ecological communities capture biologically essential resources, produce biomass; (2) its ability to decompose and recycle nutrients; (3) its stabilizing function.

Complexity has energy costs, with gradually diminishing return on investment, which can be assessed in terms of “energy return on investment” (EROI) [65]. Until now, humans have benefited from easily accessible, abundant and inexpensive energy of fossil fuels. However, energy production, innovation, and societal complexification have gradual diminishing returns [6]. The energy costs to maintain the societal structure, embedded in the terms E and μN (i.e., service sector, referred to Equation (1)), grow with societal complexification. The same trend is observed for power losses (i.e., TS in Equation (1)), as well as for the generation of multiple intermediate outputs in the societal metabolic processes. Thus, the energy consumed to perform a given ‘work’ (i.e., pV , represented by industry, as well as by all the activities related to food production) tends to decline. Moreover, also the resilience, as the “capacity to recover from a setback” will decrease [66].

With civilization development, global energy demand is getting closer to the Net Primary Productivity (NPP), which is related to photosynthesis [67,68]. The risk of regime shifts under such conditions are becoming higher. Preliminary estimates of future Total

Primary Energy Supply (TPES), expressed in watts, are based on World Energy Council forecasts [69] and total appropriation of NPP [68]. In particular, the World Energy Council (WEC hereafter) generated two different scenarios for the year 2050: Jazz and Symphony. The former is based on economic growth and secure individual access. The second, instead, is based on environmental sustainability, in turn based on coordinated policies and practices. Derived data are reported on Table 7.

Table 7. Foreseen Total Primary Energy Supply (TPES) values, expressed in units of [TW]; potential reduction scenarios (data derived from [3]).

Future TPES Esteem	Reference	Value [TW]
Total appropriation NPP	[68]	50.0
World Energy Council 1	Jazz scenario [69]	27.9
World Energy Council 2	Symphony scenario [69]	22.1

Presently, it is not possible to foresee the effects of approaching to NPP total appropriation. However, it is clear that, crossing that limit, the depletion of energy resources seriously impacts on the biosphere in several aspects. This is why, fixing the lower additive power to 31.7 TW and the upper limit to 50.0 TW, it is possible to define a system of boundaries also for energy, in parallel to the other planetary boundaries [3]. The increasing risk of regime shifts can be broadly associated to factors contained in Equation (1). The decline in the system efficiency is first observed through a declining value of pV (i.e., a decline in the component which powers the transformative dynamics of the system—see Figure 2). The second step is the reduction of services, either attributable to E (collective services) or μN (i.e., individual appropriation and use of energy resources). Globally, Table 7 indicates that a slight decline of μN is already occurring. It is important to remark here that common services (E) keep together the components and function of any social system. Thus, they should be preserved. Instead, μN is referred to the individual appropriation and use of energy resources. In fact, the potential μ refers to an energy amount per unit mass or number, such as the number of individuals within a community or a Country. An interesting parallel arises with food webs, for which increasing energy requirements are dependent on μN [70]. Population size, N , is also relevant. In fact, population growth rates influence the competition for energy resources, as well as the ability to extract them [71,72].

There is, finally, a risk connected to the lack of adaptation to the pulsing trend of energy availability. Since the publication of “The limits to growth” [73], scholars are stressing the fact that resources are limited and a major transition will occur sooner or later. Signs that nations are entering into a mature-stage of capitalism, characterized by a declining energy density throughput, were again confirmed in several works (see, for example [74]). However, society and policies exhibit a significant inertia in shifting away from the comforting paradigm of continuous growth, whereas cyclic dynamics, such as that described by the pulsing paradigm [27], are a reality. Figure 4 and associated data show that some Countries have a better performance than others. However, while worst performing Countries should, first, improve their status, all the nations should also consider, for the near future, that energy savings is anyway required, due to the declining supply connected with lower availability of fossil energy resources.

4.3. Policy Challenges

How to move towards a sustainable future for energy? Policy-makers are already transposing into policies the need of a transition toward a more sustainable energy system [13]. Several challenges, shortly summarized in Table 8, were identified.

Table 8. Summary of technical and economic/financial challenges for sustainable energy policy solutions.

Technical Challenges	Refs.	Economic/Financial Challenges	Refs.
<ul style="list-style-type: none"> • Providing affordable energy services; • Securitizing the energy supply for all; • Guaranteeing a per capita energy consumption above the minimum level to satisfy individual and societal needs; • Reducing pollution and GHG emissions, at rates lower than the ecosystem assimilative capacity; • Reducing resource consumption and improving renewable energy generation not exceeding the long-run ecosystem carrying capacity 	[75,76]	<ul style="list-style-type: none"> • Sufficient investment rate for installation of renewable generation and consumption capital stock to create a sustainable long-term renewable energy supply basis before exhaustion of non-renewables • Future consumption commitments (i.e., debt issuance) coupled to and limited by future energy availability. 	[75]

Three sustainability dimensions should be managed with appropriate policies in the energy discourse: (1) environmental dimension, since energy is extracted from the environment; (2) physical dimension (energy budget and resources allocation); (3) socio-economic dimension. These factors—connected with technology, economy, environment and the society—impact the national energy issues, as well as the multi-faceted energy planning [77].

The “environmental dimension” of energy is related to the need for preserving the non-renewable resources, while moving toward a low-carbon and sustainable societal lifestyle. In particular, an efficient energy supply is not enough. Instead, environmental impacts should be minimized through eco-efficient patterns (e.g., circular patterns, renewable resources, lower environmental support demand), using resources that are generated by the biosphere over shorter and smaller time and spatial scales. Such patterns and their dynamics can be assessed through energy accounting [78]. A study argued that economic systems behave like open dissipative systems, which extract negative entropy from the environment to compensate for continuous dissipation [79]. In his book “Universal Natural Law and Universal Human Behavior”, the same author stated that both human behavior and economic systems are driven by entropy. In particular, he claimed that the pursuit of low entropy, viewed from the perspective of human society, should be the main driver of human behavior. Low entropy is compatible with the following requirements: cleaner energy; CO₂ capture; process optimization; appropriate waste management, materials recycle and reuse [80].

4.4. Geopolitical and Social Dimensions

Presently, the most ecologically-sound economic paradigm is the circular one. However, we are still far from reaching tangible assessments and results. The most updated work, analyzing global resources dynamics, even if referred to year 2005 data, showed that only 4 Gt/year of waste are recycled. On the other side, 62 Gt/year of raw materials were processed to produce 41 Gt/year of manufactured materials [81]. Moreover, 44% of globally-processed materials are used to provide energy, thus being excluded from recycling option. In parallel, between 1950 and 2010, global average per capita material use increased from 5.0 to 10.3 tons per year [82].

Some economic sectors directly produce or induce greenhouse gases (GHG) emissions along the supply chain [83]. Market effects are often masked, since direct exposures of financial actors to fossil fuel sector are small (3–12%) [84]. However, the same study demonstrated that the exposures to climate-policy relevant sectors in Europe are large (40–54%), heterogeneous, and possibly amplified by indirect exposures via financial counterparties (30–40%). Similar studies should be extended, in order to understand the global weight of appropriate integrated energy and climate policies.

Economy is just one component of the “socio-economic dimension”. Disparities should be fought to minimize energy poverty. For such a reason, energy justice is meant “to provide all individuals, across all areas, with safe, affordable and sustainable en-

ergy" [85,86]. With respect to climate and environmental justice, this discipline is more targeted, being not originated from anti-establishment social movements and rooted on a strong academic tradition with many policy-relevant implications [87]. In order to develop a deeper understanding of this subject, several works suggest to approach to this topic through energy geographies [88], as well as to the spatialization of energy justice, which depends on "landscapes of material deprivation, geographic underpinnings of energy affordability, vicious cycles of vulnerability, and spaces of misrecognition" [89]. That is why the geopolitical dimension becomes relevant.

A variety of different approaches may be defined when talking about energy efficiency or sustainability. This plurality derives first of all from the complexity of the very topic, linked to the different levels at which energy planning can be located. For instance, dealing with an energy plant, it may be technically modelled: (1) as an enterprise, focused on its economic sustainability and profit-making performance; (2) as a piece of engineering, focused on technical efficiency; (3) as a part of a public energy network, focused on its role of local energy provider; (4) as a perturber of environmental equilibrium, focused on environmental impacts; (5) as an element for the transition to fossil-free energy, focused on short-term performance.

Moreover, different policy narratives are possible for the energy sector [90]: (1) sustainability; (2) middle-of-the-road (i.e., no remarkable shifts); (3) regional rivalry; inequality (i.e., maintaining the divide between rich and poor countries); (4) baseline (no new policies at all). These narratives need to be framed within the changing 'global energy order'. In fact, the present geopolitical framework is showing clear signs of crisis, being contrasted by national re-appropriations of the extractive industry and the expansion of emerging National Oil Companies beyond their national borders [91]. In particular, the 'global energy order' is becoming multi-polar and hybridized under some constraints: (1) the tendency of energy resources national re-appropriation, as written before; (2) the cooperation among international oil companies; (3) the development of energy service companies; (4) the definition of legal services, which contribute to international rules sophistication.

In parallel, more uncertainty depends on different strategies, which could be adopted by oil-exporting countries as a consequence of climate policies [92]. Moreover, the effects of the so-called "shale revolution" should be taken into account, especially for Countries highly dependent on oil and gas imports and where the negative economic consequences of oil prices drop are not rebalanced by sufficient buffers, like sovereign wealth funds [93]. Roadmaps toward de-oilification and de-coalification should be supported through geopolitical instruments, such as performance standards, cap and trade, and carbon tax. A performance standard is commonly viewed as a regulatory tool, in which the government sets pollution limits at the plant or unit level. An emissions trading mechanism establishes an emissions cap or limit and allows the trading of rights to emit. The carbon tax is viewed as a more efficient instrument in comparison to other mechanisms, sending similar price signals across sectors and over time and allowing for a predictable capital stock turnover.

Social acceptance plays a fundamental role in the transition toward a sustainable global energy system. Social acceptance can be supported by stakeholder engagement practices which improve communication and widen the legitimacy of sustainable oriented choices [94,95]. Moreover, narratives are important both to develop the social acceptance of sustainability policies and to deploy innovative technologies [96]. Tacit knowledge, shared narratives, user relations and learning in inter-organizational networks are key enabling factors in this process [97]. However, the support of arts as instruments of aesthetic meditation on sustainability issues can be effective to support the process of social acceptance [98].

4.5. Potential Strategies and Research Needs

How can these dimensions meet the requirement of social-ecological stability from an energy perspective? Which are the most probable changes or possible strategies? First, the present level of power production, consumption and losses depends on the societal

structure and functions. It is difficult to think of a reduction of resources use without any societal impact. A study highlighted several alternative options to cope with energy problems [99]: (1) Resource consumption reduction, which is constrained by the relation between complexity, requiring energy and societal problem-solving abilities; (2) Consumption control through price mechanisms, which still doesn't touch the need of increasing consumptions for problem-solving; (3) Resources rationing, which is socially unacceptable, if not during short-period and under critical; (4) Population reduction; (5) Technological solutions. Furthermore, another lever in this direction may be the exploitation of potential energy savings, driven by consumer behavioral changes [100], which the European Environmental Agency (EEA) itself identified as a key strategy for energy efficiency [101].

None of these seem to easily pursuable, but—most of all—none of these would provide (if taken alone) the necessary leveraging action towards a multi-level, multi-dimension and hugely complex sector like that of energy, which by definition encompasses all the three traditional sustainability dimensions, namely, environment, society, economy.

Different operational options might be investigated under the light of Sustainable Development Goals (SDGs). In particular: goal 7: ensure access to affordable, reliable, sustainable and modern energy for all; goal 8: promote inclusive and sustainable economic growth, employment and decent work for all; goal 9: build resilient infrastructure, promote sustainable industrialization and foster innovation; goal 12: ensure sustainable consumption and production patterns. Solutions and implications, shortly listed in Table 9, are indicated on the basis of Equation (1), Figures 4 and 7. In particular, Figure 7 shows that pV (industry, agriculture, fisheries) is declining, together with residential sector μN expenditure. In parallel, common services (E) and power losses (TS) are growing. Figure 5 shows that some Countries are more performing than others, considering their efficient power consumption with respect to their power supply.

Table 9. Extracts from Sustainable Development Goals, directly related to energy, with solutions or implications derived from this paper, with special reference to Equation (1) and Figure 6.

Sustainable Development Goals	Solutions or Implications
Improve efficiency (Goals 7, 8, 9, 12)	<ul style="list-style-type: none"> • TS reduction; • Reduce the number of intermediate product outputs and non-energy use consumption, which do not contribute to final system efficiency
Decouple economic growth from environmental degradation (Goal 8)	<ul style="list-style-type: none"> • Apply physics-based efficiency indicators, not influenced by market trends; • Apply and develop coupled bio-physics and socio-economic accounting approaches rooted on bio-physical dynamics accounting, which consider the multi-dimensional nature of human societies
Focus on high-value added and labour-intensive sectors (Goal 8)	<ul style="list-style-type: none"> • Improve the share of energy consumption in favour of industry, agriculture and fisheries (pV) or common services (E), while reducing the individual appropriation (μN)
Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption (Goal 12)	<ul style="list-style-type: none"> • In relation to fossil fuels, reduce both energy losses and the generation of intermediate product outputs and non-energy use consumption, which do not contribute to final system efficiency
Upgrade the technological capabilities (Goals 7, 9)	<ul style="list-style-type: none"> • Reduce system energy losses related to energy production and distribution (TS)

Considering sectoral subdivision of global energy consumption (Figure 7), the most urgent interventions pertain power plant losses and household sectors. These actions mainly relate to efficiency improvements. A different share among sectors should be planned, considering also the need of focusing on high-value added and labor-intensive sectors (SDG goal 8). In order to enable a higher consumption for technological development and upgrade, as well as for food production, the future growth of terawatt consumption by some sectors needs to be limited. Many experts believe that global efficiency improvements and reduced demand would be the best solutions to cope with the existing “physical dimension” [102]. Efficiency improvements should start from reducing power plant losses. Their global amount is almost stable, representing a 20% of the final energy consumption. However, it would be desirable to reduce them at least of 2–3%, fixing a target to 17–18%. Technological solutions are available [103] and they can be integrated into energy production and consumption systems [104]. The technological upgrade of distribution networks would be also relevant with respect to this target. Better results could be gained by re-designing the societal energy processes, reducing the number of the number of intermediate product outputs and non-energy use consumption, which do not contribute to the overall final system efficiency. Several factors should be considered in planning this action: (1) the need of increasing the electricity generation infrastructure, which might not be enough to meet the global demand of energy, under a business-as-usual scenario, for year 2050 [105]; (2) the efficiency of technological alternatives [106]; (3) the quantification of eco-efficiency indicators with respect to selected alternatives, which allow the evaluation of impacts related to undesirable outputs [107,108]; (4) the costs for different solutions [109].

It is important, however, to stress that multiple rebound effects might lead to a different result from the expected one [110]. The need of increasing pV, associated both to industrial and to food productions, will be a natural consequence of the increasing world population trend. Thus, the present allocation percentage will likely become higher than the present 21%. Also, the allocation percentage related to common services (E) should be, at least, preserved. Digitalization, ICT and world connectivity might limit this growth, if their role and potential applications are better understood. For example, material flows and workers’ transfers could be reduced and substituted by a better coordination of logistics and by an information exchange system to support a lower mobility for working purposes. Considering the necessity of transition toward a low-carbon future, a dispersed production of low-gain energy by small communities or even individual households would be a desirable option [111]. In this respect, some elements of discussion were introduced [6]: (1) an information-centered economy and society, where material flows are reduced; (2) a gradual delocalization of power generation and distribution systems, together with dispersed settlements and smaller production chains, which would be enabled by ICT support. This might imply a potential reduction of energy consumptions for the transport sector, which was accounted here as common services (E). In fact, human and resources movements would diminish, if an optimization compromise is reached. Urban centers would also benefit from a decongestion.

Household energy consumption, displaying a declining consumption trend, still has margins of action. Then, it is easily foreseeable that a reduction of a further 2% is not impossible. Several solutions, like more efficient illumination and passive thermal regulation, are already widely applied in many Countries. Widening this action would allow to reallocate 4% of the present global consumption share, derived from household consumption and power plant losses decline, on other critical sectors. Measures related to households should be implemented, considering that: (1) consumers psychology and behaviors strongly influence the willing to implement private energy savings and efficiency actions [112,113]; (2) behavioral shifts, which are more easily modifiable should be promoted first, introducing simplifications aimed at promoting desirable decisions, while implementing money-saving alternatives [100]; (3) the implementation of education and communication campaigns seems to be among the most efficient means for promoting the adoption of sustainable household’s resources consumption patterns [114]; (4) actions directed toward low-income

areas could play a significant role within this target [115,116]; (5) ICT solution can support behavioral changes in relation to inefficiency removals and energy saving [117,118]; (6) direct and indirect factors should be carefully analyzed when determining the carbon footprint of different options in search of eco-efficient solutions [119].

Further analyses are necessary to determine and quantify the potential solutions, since complete and reliable data are presently missing. Behind these points, the concept of energy efficiency, presenting the contrasting physical and economic perspectives require to be clearly defined, considering the necessity of decoupling economic growth from environmental degradation. Moreover, it should be considered that we adopted a simplified and incomplete version of thermodynamic equations, implying a simplified epistemology necessary to develop an easier phenomenological conceptualization for the empirical laws, verified in the literature, that can be applied social-ecological systems. This is true, for example, in the case of the product pV , that we used as a simplified indicator for work. This version, however, would be valid only in the absence of nuclear, magnetic, electrical, and surface tension effects [120]. Otherwise, other forms of work should appear in the equation, like the shaft work, which could be determined for the system. In our case, the use of the simple products pV and TS for representing work and power loss, respectively, is not always accurate from an engineering point of view, since the computation of the quantities actually depend on the change on volume and entropy, respectively. Moreover, the form assumed by a certain amount of produced work may not be representable as the product of a pressure times a volume, and the entropy (intended as change of net entropy) may depend in turn on the details of the transformation in terms of heat transfers. Despite this apparent inappropriateness, we chose to use this language since it may directly refer to the symbolism used in the discipline of econophysics, where a set of isomorphic relations are built up between economic and thermodynamic and statistical mechanics laws [121,122]. The application of such an approach allowed to develop a phenomenological conceptualization for the empirical laws of economics. Therefore, the epistemology we used to connect socio-economic or environmental narratives to thermodynamics should not be intended as a strict identification of the single quantities, but rather as a convenient conceptualization of the overall body of knowledge concerning the global energy systems.

The role of cities, as most densely populated areas in the world, should be rethought [123]. Meanwhile, rural areas could benefit from a 'renaissance', which would enhance the natural, social, cultural and economic potential of rural areas. The European Union already promoted a research area on this topic through HORIZON 2020 programme. In particular, it will be interesting to observe the outcomes of the projects aimed at designing innovative policy instruments, approaches and governance models, through which socio-economic and environmental conditions should be improved. However, any option should be supported by further research, aimed at modelling different scenarios, their likelihood, as well as impacts. Energy sectorial accounting should start to disentangle shared and individual energy consumptions. Moreover, the impacts of ICT require to be assessed at different scales.

Further researches are also needed, in order to better understand the energy dynamics of human SES and for reducing the potential risk of a future societal collapse. In fact, such dynamic modes are still at embryonal level due to their complexity. However, with this respect, nexus modelling might offer some hints. In this field, a huge number of works was published in the last years [124–126]. Energy pressures on the environment should be determined at different spatial scales. An improved integration of data, derived from human SES energy structure and its footprint, would support better planning tools development, which would become available for policy-makers and public managers. The development of big data management and a more efficient ICT-based integration might be useful in such a direction.

Finally, studies are necessary to better integrate the energy sector in the broader economic and financial landscape. In particular, the shape of this network structure, the interconnectedness among producers, the financial interdependence of electricity markets

players, as well as the consequences of the existing structures and dynamics, should be considered [127]. The outputs of these inquiries should become effective inputs for future policies, managed by an international energy governance structure, whose existence is of paramount importance to drive the transition toward a sustainable civilization and human lifestyles dynamics.

5. Conclusions

This paper, starting from an assessment of the basic energy features of a human Social-Ecological System (SES) from a physical perspective, analyses present energy data and the existing risks for the future of ecological civilization, inferring some policy-relevant implications, as well as research needs. In particular, global energy system data can be described through basic indicators (i.e., production, consumption and efficiency). Results showed that two key constraints, derivable from physical principles, exist on the global energy system. The first is availability, the second is a relation between availability and consumption, being derived from the least action principle in its thermodynamic form. In particular, efficient consumption values can be seen in relation to supply, while final consumption can be decomposed into components (i.e., 1. power converted into work, associated to industry, agriculture and fisheries; 2. power to feed the internal societal metabolism, as both individual and shared services; 3. power dissipation). The latter term is growing due to the complexification of economic structure. The higher costs in terms of resources to feed up the development of human civilization are paid by the environment. This is why human SESs are moving toward undesirable tipping points, which are well described within the planetary boundary framework. Nonetheless, neither inexorable progress nor unavoidable collapse are pre-determined futures. Instead, different solutions are possible. These solutions imply different challenges, whose relevance is also derived from SDGs. The relation between solutions and different multi-dimensional policy options are summarized in Tables 9 and 10.

These constraints act within a system with prevalently finite resources. In fact, from one side, fossil resources, that are non-renewable, have a limited availability and their extraction trend obeys to a logistic curve. On the other side, renewable resources are constrained by a complex dynamics governed by specific thermodynamic equations, according to which a maximum limit of biomass production is possible. Since the current trends of human appropriation of net primary production of the biosphere are increasing, anthropogenic activities are already generating a visible impact on the biosphere. This is also confirmed by the current planetary boundaries indicators. On the other side, there are two related physical constraints, associated to the growth of complexity of social-ecological systems. The first one is the increase of energy costs to maintain the structure and functions of a complex society. From one side, this is proved by the increasing diminishing returns on energy investment, as confirmed by the literature. On the other side, complex systems components balance their energy use according to the least action principle (known as maximum empower principle in system ecology). The existence efficient power, relating energy supply and consumption through an efficiency-like indicator, implies a constraint between consumption and desired efficiency of the system, meaning that maximizing the efficiency of the system might impact on the sectorial structure of final consumption. With this respect, some new evidences are introduced on Country-level energy performance and its necessary improvements and potential sectoral action at global level. Basically, our findings indicate four areas of future action: (1) redefine sectoral energy distribution shares; (2) improve Country-level performance, if needed; (3) reduce intermediate outputs and non-energy final output; (4) reduce also resources supply to improve the eco-efficiency. Even if these solutions are not fully quantified, a redistribution of final consumption shares, derived from a 4% reduction of power plants losses and household sector, would be desirable.

Table 10. Multi-dimensional (environmental/technical; economic; governance) energy policy options with respect to identified challenges and SDGs. Behind this study, different references are used to compile this table. They refer to: (i) Environmental and Technical solutions; (ii) Economic dimension; (iii) Governance dimension.

Environmental and Technical Dimension	Economic Dimension	Governance Dimension
<ul style="list-style-type: none"> • Improve the physical efficiency, reducing energy losses and limiting intermediate products, as well as non-energy products; • Improve the performance and increase savings, gaining a better system eco-efficiency • Increase the use of renewables; • Focus on de-oilification and de-coalification of economy; • Sectorial consumption redistribution; • Improve information sharing, while reducing materials flows; • The efficiency of energy conversion system; • Reduction of energy consumption (in particular for private purposes); • Technological upgrade of power plants and energy distribution system; • Elimination of wasteful use of energy for luxury goods, transferring resources to productive functions; • Increase of non-intensive agriculture; • Improve the quality of buildings 	<ul style="list-style-type: none"> • Circular economy roadmaps development; • Exert a control on financial markets, which are primary drivers of product flows, as well as energy consumption; • Control oil prices, in order to reduce the adverse impacts during the transition phase 	<ul style="list-style-type: none"> • Support climate policies; • Develop international energy governance structure, which should be able to act as control system at the same scale of present biophysical and socio-economical flows; • Population control and relocation • Reduction of economic enterprises and people concentrations in cities • Develop educational solutions to prepare children for their lower energy future

It is important to consider that no solution ‘on the shelf’ exists, due to the interconnected and complex nature of global energy system. Decades of attempts by governments, politicians, economists, technologists and intellectuals to reverse—or at least slow down—the geobiosphere and the human society decline appear to have had no result whatsoever. The intrinsic reason for that must be searched in the complexity of the global problems we all have to face now. Only integrated, interdisciplinary and likewise complex conceptual and quantitative tools can provide the sufficiently comprehensive insight for coming to good policy-making options. Parallel approaches are also required to verify the viability of the proposed options from a policy perspective, some of which are discussed in this paper. Thus, we summarize some relevant policy issues in Table 10.

Some new evidences were introduced in the analysis at Country-level energy performance, where necessary improvements and potential sectoral action at global level were identified. Basically, our findings indicate four areas of future action: (1) redefine sectoral energy distribution shares; (2) improve Country-level performance, if needed; (3) reduce intermediate outputs and non-energy final output; (4) reduce also resources supply to improve the eco-efficiency. Even if these solutions are not fully quantified, a redistribution of final consumption shares, derived from a 4% reduction of power plants losses and household sector, would be desirable.

As a concluding remark, the social dimension of sustainability and, in particular, social equity, must be a relevant criterion for future energy policies. This is why we quote the words by H.T. Odum: “Trade and projects that unbalance local economies [. . .] and increase energy inequity between countries, do not maximize the world economy, because they leave major sectors of the world’s population in poverty, essentially outside the world economy. This pattern wastes resources into luxury and excess of the developed countries, diverting resources that used to go directly to population support (without payments) [. . .]. This pattern is not sustainable, does not maximize world wealth and emergy, does not reinforce world production, and will not last. These patterns will become discredited as world opinion changes, as revolutions occur, and worldwide resource depletion soon

cuts off the largesse of the overdeveloped countries". The transition toward a sustainable and equitable post fossil fuel low-carbon society should be carefully planned through appropriate policies. These, in turn, should be transformed into actions, considering human well-being and a gratifying sufficiency for everyone as goals, together with the preservation of the environment, which guarantees the survival of the biosphere.

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Abbreviations

This section contains a list of symbols and acronyms together with their basic definition.

Symbols and acronyms	Definition
G	Gibbs free energy
GDP	Gross Domestic Product
GHG	Greenhouse gases
Gt CO ₂ -eq	Gigatonnes of carbon dioxide equivalent (unit of measure of GHG emissions)
IEA	International Energy Agency
Mtoe	Million tons of oil equivalent
NPP	Net Primary Production
OECD	Organisation for Economic Co-operation and Development
P	Efficient power
SES	Social-Ecological System
TPES	Total Primary Energy Supply
USD	US Dollar
TW	Terawatt
WEC	World Energy Council
η	Efficiency-like indicator, as ratio of power output (i.e., power final consumption) and power input (i.e., power supply)

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