INVESTIGATION OF THE IMPACT OF ENERGY DYNAMICS ON SUSTAINABLE DEVELOPMENT

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Abstract. This paper has in view to investigate the energy dynamics over time and to evaluate the effects of past energy options on the progress towards a sustainable development, together with the influence of sustainability goals on future energy strategies. Throughout the paper several issues relating with the sustainability criteria for energy are examined and the bi-univocal relationship of interdependencies between energy and sustainability is highlighted. An analysis is performed concluding that the development of renewable energy sources is the best compromise for future energy developments.

1. INTRODUCTION

Energy is of paramount importance for economic development, reducing poverty, improving human welfare and essentially shaping the living standards of the modern society. Energy poverty is one of the most important drivers of poverty, as it refers to the lack of access to electricity, modern ways of heating and cooking, access to education and health services, food security and rural development. Yet many patterns of energy production, distribution and use rely on unsustainable practices, therefore lessons of the past must be understood and used as guidelines for future strategies.

Sustainable development is a three-dimensional concept that refers to the balance of three facets: economic growth, social development and environmental protection [1]. Energy is a key issue in the pursuit of sustainability, as major environmental damages are related with the extraction, production, distribution and use of energy. The environmental footprint of energy span from air, soil and water pollution, to the emissions of CO_2 and other green gas gases (GHGs). Moreover, the achievement of the three-dimensional goal of sustainability dramatically depends on energy choices and options industry and consumers are making, but this relates also with specific policies, legislation and regulations associated with energy issues.

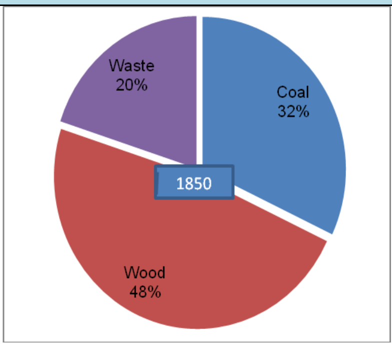
At the moment, an interesting bi-univocal relationship between energy and sustainable development is shaping. If the past was characterized by the impact of energy on sustainability, sustainable development goals will be the main factors that will lead to the adjustment of energy patterns in the future. Therefore, the forthcoming energy options will strongly depend on sustainable criteria. Consequently, this paper investigates the energetic context over time, from the rising of industrial activity to present time, highlighting the emergence of a dynamic bi-univocal relationship between energy and sustainability and the way in which whole energy chain and environmental protection may become compatible goals.

2. CRITICAL ANALYSIS OF THE ENERGY DYNAMICS

The development of the global energy market took place gradually from the XVIII century, when the consumption was centred on the utilization of natural resources, mainly wood. From XVIII century to present, successive waves of technological discoveries led to the better usage of other energy sources in a very rapid transition (see figure 1).

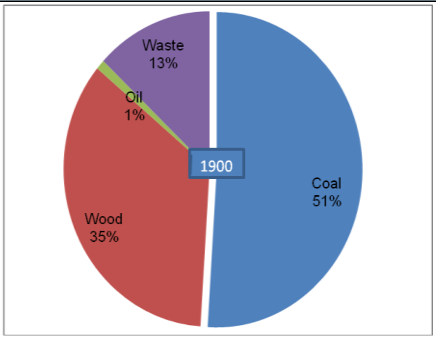
Up to 1770: Main fuel used: Wood

INDUSTRIAL REVOLUTIONS



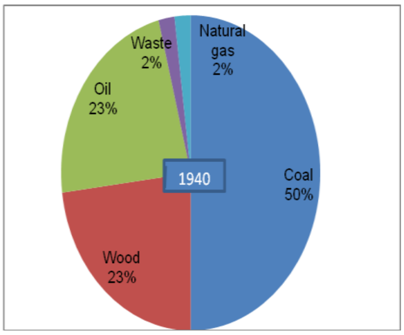
1770 – 1850
Main fuels used: Wood + Coal

Reason of substitution:
Technological transformation I
(the use of steam power)



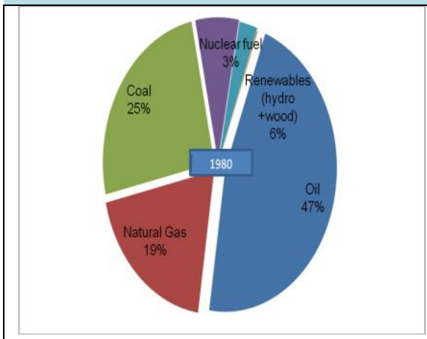
1850 – 1930
Main fuel used: Coal

Reason of substitution:
Technological transformation II
(the use of internal combustion engine, electrification, development of industry)
CO_2 concentration: 290 ppm (1860-estimation)



1930 – 1960
***Main fuels used:* Coal + Oil**
Reason of substitution:
Technological transformation III
(development of synthetic materials)
CO_2 concentration: 316 ppm *('59)*
the 1st systematic measurements, Mauna Loa, Hawaii

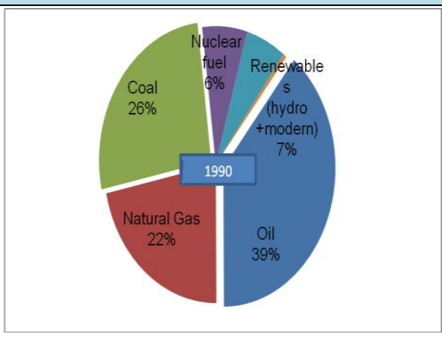
DEVELOPMENT OF INDUSTRIES AND TRANSPORT



1960 - 1980

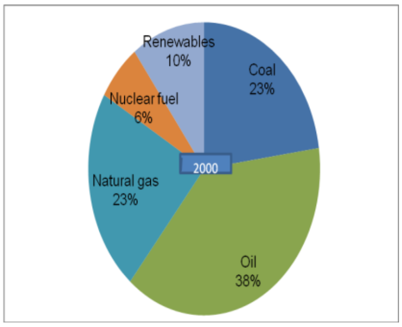
***Main fuels used:* Oil + Coal**

Reason of substitution:
Technological transformation III'
(development of electronics; introduction of nuclear power)
CO_2 concentration: 330 ppm ('72)



1980 - 2000
Main fuels used: Oil + Coal +Natural gas

Reason of substitution:
Technological transformation IV
(development of computers, telecommunication, transportation)
CO_2 concentration: 356 ppm ('92)

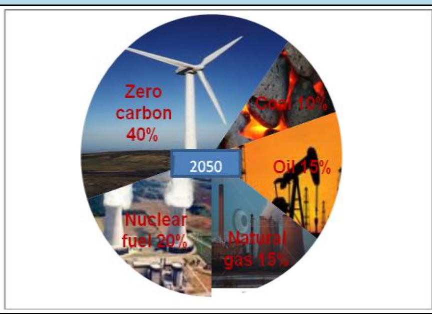


2000 - 2010
Main fuels used: Oil + Coal +Natural gas

CO_2 concentration:
371 ppm (2002)
390 ppm (2010)

DEVELOPMENT OF NEW TECHNOLOGIES AND LEGISLATION

Possible future developments
Main fuels used:
Zero Carbon: renewable + new technologies
Reason of substitution:
Technological transformation V
(new technologies based on new and renewable energy sources, cost-effective technologies, energy efficiency plans)



Technological and legislative transformations

Figure 1. Chronological substitutions of primary energy options and their effects on environment (the percentages representing the examples for energy mixes are given in market share %).
Source: data for the energy mix are processed from [2] and [3] and the data for CO_2 concentration from [4].

Still, in the later years the interest on natural resources knew a rebirth, and the concerns about the scarcity of fossil fuels and their future exhaustion correlated with their rising prices, pollution and climate change placed the focus on renewable sources of energy (RES).

The first energy transformation was linked with the substitution of wood by coal as a primary energy source, as a result of the invention of the steam engine. This constitutes the 1st industrial revolution, which was based on technological transformations linked to a new energy source. Gradually, the wood was replaced by coal, until another invention made its way on the market, namely the internal combustion engine. This 2nd industrial revolution was based on the gradual substitution of coal by oil as a primary energy source, and introduces a major technological transformation based on a new source of energy. The adequate provision with energy sources was linked with the economic development since the 1st industrial revolution, but their drawbacks were not yet taken into consideration.

The next waves are characterized by the development of industries, namely synthetic materials, electronics, convergence of computers and telecommunications and also transportation. Especially after the 2nd world war, the energy sector was viewed as a state controlled sector and large energy companies become known, like Electricite de France and Gas de France (1946) in France, and ENEL (1962) in Italy. During the '60s a new energy source came alive, namely nuclear energy, but its weight in the energy mix has not been dramatically changed during time, due to concerns related to its vulnerability. The oil shocks of 1973-1974 and 1979-1980 have generated concerns about the energy resource scarcity and state interventions into the energy sector, together with the first national energy policies and implementation agencies. These two events came with the first concerns about the environment, but only in terms of reducing wastes and emissions of specific pollutants. The climate change issues were in focus only after the 1990, when the importance of GHGs was acknowledged and waste recycling and specific regulations came into force [5].

The XXth century was a period of exceptional economic growth and phenomenal increase of energy consumption characterised by a continuous improvement of living conditions, but these encompassed a tremendous cost on environment. The increasing awareness in climate change concurred with the finite resources of fossil fuels and their rising prices led to the consideration of RES. However, the contribution of RES to the global and even European primary energy mixes was and still is modest in comparison with their technological and economic potential. The first forms of RES that were considered were wood and hydropower, later followed by modern types (as wind, solar, biomass, geothermal, small-scale hydropower, etc). Their contribution to the energy mix grew from 6% in the 80', to 10% in the first years of the new century. Unfortunately, in 2009, RES contribution remained at only 10% of primary energy balance of the declared pioneer in this sector, EU (27), [6] and the main part was still coming from hydro energy. The EU (27) self-imposed 12% of RES by 2010 failed to be achieved, but signals the European commitment and the need of further development of various projects based on RES.

The XXIst century is an era of exponentially increasing demand for energy, ceteris paribus, considering the evolution of the globalized economy, therefore a sustainable energy future is needed. The concerns about the sustainability goals will have an impact on energy choices, and not the other way around like in the past. Consequently, the 5th technological transformation relates with the future and it will concern both industry and consumer, due to the emergence of new industrial technologies. This wave will be characterized by the transition to zero carbon resources (by 2050, 40% of the primary energy sources will be based on renewables or new environmentally friendly energy), only if the policy makers will come as a strong support of this environmentally optimistic scenario, both with appropiate legislation and long-term investments. This technological transformation is the most complex so far, involvind a true revolution in the energy sector. This wave involves sustainable energy solutions and might reffer to a combination of the followings:

1. energy savings (e.g. better insulations, better lighting solutions, improved electric motors);
2. energy efficincy plans (e.g. combined heat & power, the development and use of vehicles of increased energy efficiency);
3. cost-effective technologies;
4. the development of RES of 2^{nd} and 3^{nd} generation together with the development of smart-grids;
5. the use of new forms of energy, as hydrogen and nuclear fusion together with the development of related infrastructures;
6. better technologies for the use of fossil fuels (for instance fossil fuels energy combined with affordable and reliable carbon capture and storage).

While the first three solutions are normal ways of maximizing the energy capital, for the last three, future holds the answer. There are three categories of RES, depending on their position on the market lifecycle: 1^{st} generation technologies that are reaching maturity (as hydropower, 1^{st} generation biomass), 2^{nd} generation technologies that are imposing on the market (as wind energy, solar energy – photovoltaic and thermal – 2^{nd} generation biomass based on waste, biofuels from non-food crops), 3^{rd} generation technologies that are in the launching step (as tide & wave energy, concentrating solar power, nanotechnology) [7].

This is a formidable challange, as the new forms of energy or new technologies must satisfy the rapidely growing demand, and today about 85% of energy comes from fossil fuels [8]. Therefore, future energy research & development must receive a particular attention from business and legilative bodies. A more detailed analysis of the possible alternatives for future is further presented throughout section 3.

Moreover, the technological diversity of the future will also depend on the local energy needs and available energy sources of certain communities and regions. Flexible arrangements, balancing small- and medium-sized with large-sized scale energy facilities are feasible future solutions.

The potential effects of the energy substitutions of the past on enviroment are also shown in figure 1, in terms of CO_2 concentration (expressed in parts per million - ppm). From 290 ppm in 1860, it increased with 100 ppm by 2010, to a value of 390 ppm [4]. A significant amount of this 34% increase is associated with the CO_2 emissions from the usage of fossil fuels (coal, oil and gas). Generally, the CO_2 emissions from the usage of fossil fuels account for about 57% of the total CO_2 emissions [9], therefore the environmental constraints should be considered when dealing with energy demand.

3. ANALYSIS OF ENERGY OPTIONS DEPENDING ON SUSTAINABILITY CRITERIA

Sustainability criteria for energy refer to indicators that link energy and the sustainability triangle in terms of mixes of economic, social and environmental criteria, showing a very complex interdependence. In terms of sustainable energy planning, literature shows the use of complex methods that are based on multi-criteria decision making as analytical hierarchy process (AHP), outranking techniques like preference ranking organization method for enrichment evaluation (PROMETHEE) [10], elimination and choice translating reality (ELECTRE), iterative decision support systems and fuzzy set theories [11]. However, the use of both quantitative and qualitative evaluation criteria, often conflicting, together with the uncertainty of providing exact numerical values led to a rather intractable and unstructured picture. The sustainable energy decision making has not yet fully developed a systematic methodology that is able to combine quantitative and qualitative inputs from engineering studies of risk, cost, and benefit, together with all stakeholders' views and values. Therefore, the purpose of this section is to present a straightforward, yet a suggestive analysis, based solely on qualitative criteria, which may be confined within the imposed limits of this paper.

As documented research shows that is impossible to define absolute sustainability criteria [12], corroborated with the fact that sustainable energy projects are very complex, five major classes are defined in the context of this work, involving a mix of economic, technologic, ecological, social and vulnerability criteria. This analysis involves five criteria set and five technical future alternatives that were previously identified as energy solutions belonging to the future technological wave (see figure 2).

The selection of the most appropriate energy source and technology depends on balancing the sustainability criteria and the optimal solution is decided by a straightforward judgment. The methodology adopted for this paper involves the association of each criteria set with qualitative measures translated into utilities ranging from 0 to 1 (0 showing the least favourable and 1 the most favourable alternative for a certain criterion, in 0.25 increments). The alternatives are ranked depending on the global utility, acquired by considering the sums of individual utilities obtained for each alternative.

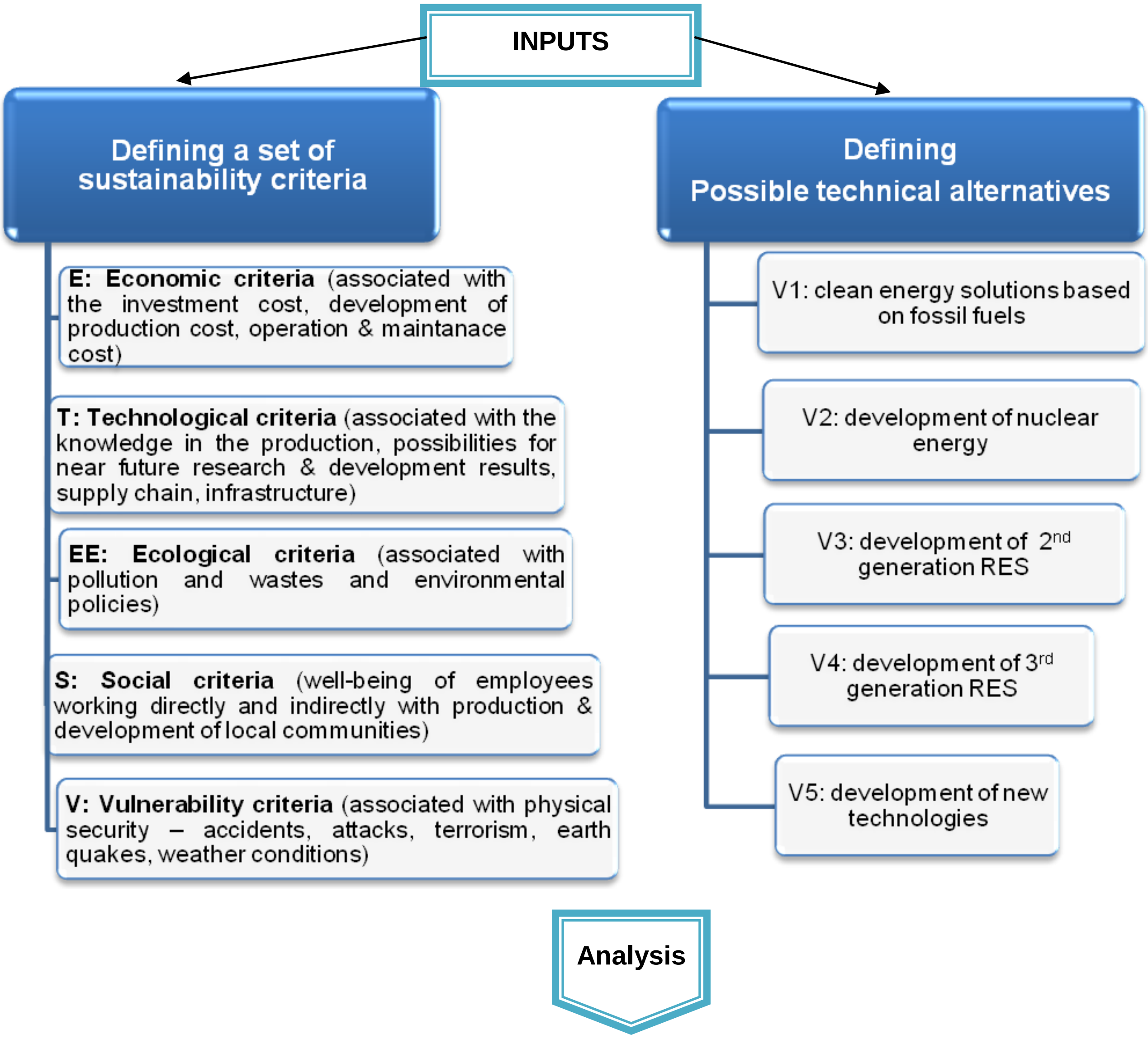
For *E (economic criteria)* the best future option is considered V2 (nuclear energy) as it is the best known technology to date from the considered alternatives. The second option is considered V3 (2^{nd} generation RES) as it is a well-established technology, but requires a smart-grid. Next scores V4 (3^{rd} generation RES) as it is still at the prototype stage, and last comes V1 (clean energy solutions for fossil fuels) that are considered the least affordable technologies.

In the case of *T (technological criteria)* the best future option is considered also V2 for the same reasons as above, followed by V3, V1, V4 and V5, depending on the knowledge in production and supply chain, together with the development of specific infrastructures.

For *EE (ecological criteria)* the scores are awarded decreasingly from V4, V3, V5, V2 and V1 taking into consideration the possible emissions, direct and indirect, wastes and consumption patterns (for instance in the case of V5 the development of electrical vehicles are considered; the automobile does not directly produce any emission, but the charging of the battery involves consumption of electrical energy, that might be unsustainably obtained, leading to indirect emissions).

In the case of *S (social criteria)* the alternatives are ranked depending on their social acceptance and safety of employees working directly and indirectly with production and local communities. V4 is the best alternative, followed by V5 and V3 (as some persons are still reluctant at large wind farms and biomass use). V2 comes last as the nuclear energy is the only type of energy related with the "not-in-my-backyard" (NYMY) attitude from communities.

The *V (vulnerability criteria)* judges the alternatives from the point of view of their exposure to risk from various sources, including bad weather conditions, earth-quakes, and attacks. The best option from this point of view is considered V4, followed by V3 (as it depends on specific weather conditions), V5 (as hydrogen and related infrastructure is considered as a technology in operation), V1 (correlated with the safety of carbon capture and storage) and last comes V2 (taking into consideration the global results of a possible accident involving nuclear facilities).



Sustainability criteria / Technical alternatives	E	T	EE	S	V	Global utility	Ranks
	Individual utilities						
V1	0.25	0.5	0	0.25	0.25	1.25	5
V2	1	1	0.25	0	0	2.25	3
V3	0.75	0.75	0.75	0.5	0.75	3.5	2
V4	*0.5*	*0.25*	*1*	*1*	*1*	*3.75*	***1***
V5	0	0	0.5	0.75	0.5	1.75	4

OUTPUT
Optimal alternative: **V4**
Ranking: **V4PV3PV2PV5PV1**

Figure 2. Analysis of energy options depending on sustainability criteria.

The results acquired for global utilities show that the best alternative for future is V4, which scored a global utility of 3.75. The individual utilities for EE, S and V criteria proved that is best fit for environment.

The best results are obtained for RES belonging to 2nd and 3rd generation. The optimal alternative corresponds to the best compromise and is represented by the development of RES belonging to the 3rd generation. The ranking is also shown ranging from the best one, V4, to the worst one, V1, (where V4PV1 means that variant V4 is preferable to V1). Nevertheless, the considered types of RES, although still at the prototype stage, is of greater interest than clean fossil fuels technologies, as insert better into the environment than the latter. The nuclear energy still plays an important part, as the technology, related wastes and their disposal are best known from the considered alternatives. However, these results might be affected by recent global events related with concerns regarding nuclear energy.

4. CONCLUSIONS

This paper investigated the energetic context over time, from the rising of industrial activity to present time, highlighting the impact of energy on sustainable development through four technological waves. The fifth technological wave belongs to the future, and this time, the energy options will be shaped by sustainability goals. This critical analysis shown that between the three-dimensional goal of sustainability and energy options there is a worthy of note bi-univocal relationship. If the past was characterized by the effects of energy options on sustainable development, the future is energetically shaped having in mind sustainability criteria. To investigate this relationship, a straightforward qualitative analysis was performed considering five sustainability criteria and identifying five possible feasible alternatives for the future. The analysis showed that by balancing all the sustainability goals, all types of RES, although some still at the prototype stage, are of greater interest than clean fossil fuels technologies. Nevertheless, the technological diversity of the future will depend on other important aspects, like the local energy needs and available energy sources of certain communities and regions. Flexible arrangements, balancing small- and medium-sized with large-sized scale energy facilities are seen as feasible future solutions.

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