Sustainability **2011**, *3*, 1855-1865; doi:10.3390/su3101855

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Sustainability Science: Sustainable Energy for Mobility and Its Use in Policy Making

Fabio Orecchini [1,*], Adriano Santiangeli [2] and Valeria Valitutti [1]

[1] CIRPS (The Interuniversity Research Centre on Sustainability Science), Sapienza University of Rome, Piazza San Pietro in Vincoli 10, Rome 00184, Italy; E-Mail: valeria.valitutti@uniroma1.it

[2] DME (Department of Mechanics and Energy), Guglielmo Marconi University, Via Virgilio 8, Rome 00193, Italy; E-Mail: a.santiangeli@unimarconi.it

***** Author to whom correspondence should be addressed; E-Mail: fabio.orecchini@uniroma1.it; Tel.: +39-06-44585-400; Fax: +39-06-44585-779.

Received: 30 July 2011; in revised form: 9 September 2011 / Accepted: 13 September 2011 / Published: 12 October 2011

Abstract: Since the 1980s sustainability has clearly become the challenge of the 21st century. In a process toward a sustainable society it is crucial that different stakeholders start collaboration and exchange ideas with technicians and academics. To finalize the policy decisions on important issues such as energy sustainability, collaboration between policy makers, academia and the private sector is important. This work intends to give Italian policy makers concrete advice and solutions to develop energy systems for mobility. The analysis proceeds from the context of Sustainability Science, a new science, which has emerged as one of the most important disciplines of international scientific research. Using a new approach, trans-disciplinary and integrated, this research is oriented to study and understand the complexity of the interactions between economy, society and nature. This broad approach permits proposing concrete solutions to complex problems locally and globally. We propose a scheme of definition of Sustainability Energy, defining five pillars of reference, and we redefine the energy systems for mobility in the context of Sustainability Science. In this paper, we start from the idea that we are living in a crucial passage, we are moving from the era of petroleum to the era of energy vectors. Energy systems, including mobility, should be redefined within this new approach.

Keywords: sustainability science; sustainability energy; energy systems; renewable resources

---

1. Introduction

The term sustainability has fast become a buzzword. What effectively sustainability means, how to define it, how to achieve it, is constantly discussed in the scientific and academic arena. However, the theoretical discussion on sustainability clashes with the difficulty of achieving tangible results and actively involving it in a process of real change by the main actors: civil society, the private sector and the policy-makers. Moreover the reductionism that results from the mono-disciplinary fragmentation of scientific knowledge has proved its inadequacy when researching and looking for solutions to the complex issues of sustainable development. Sustainability Science has the ambitious aim of overcoming these limits and links the scientific understanding of human–nature systems with action, in order to achieve sustainability. Sustainability Science has three main innovative characteristics: first, it addresses complexity with a trans-disciplinary approach. Second, it is problem-driven and it uses both scientific and local knowledge to resolve contextualized problems. Third, it promotes the active involvement of the different stakeholders, civil society, the private sector and policy makers, in a process of scientific co-production. To face the topic of sustainability energy, we need an integrated and trans-disciplinary approach for clarifying how to achieve a good legislation regarding the energy for mobility. We use the research experience to give advice to legislators and policy makers with the aim of finalizing the legislation toward a sustainable society, starting with defining sustainability science, energy sustainability, energy systems, energy vectors and electric vehicles.

2. Sustainability Science

The term "sustainability science" first officially appeared in a study conducted by the National Research Council's (NRC) Board on Sustainable Development in 1999 titled *Our Common Journey: A transition towards Sustainability* [1]. The Board named *sustainability science* the research agenda for supporting the transition towards sustainability. At that time sustainability science represented a noble declaration of intentions but it was not precisely defined. However it was already clear that sustainability science needed to overcome the tensions between highly focused and broadly based research, between problem driven research and disciplinary one, and between universally generalizable results and localized knowledge, problems and solutions. Moreover, the report stated that sustainability science had to be integrative and had to be committed to bridge the barriers between traditional modes of inquiry [1]. The NRC's Board definition of *Sustainability Science* was the result of years of debates on sustainable development and the result of a long-lasting growing scientific awareness on environment–society complex interaction, but it was also the first formal definition of an emerging field of inquiry that, at that time, did not have any guarantee of reaching maturity and academic recognition. At present, ten years after its first formalization, sustainability science has become an international and recognized field of inquiry supported by an increasing number of institutions, programs and scientific journals. Clear evidence of this vital process of knowledge structuring has been the establishment of Sustainability Science as one of the sections of the journal Proceedings of National Academy of Science (PNAS) in 2006 [2] and the launch of the journal Sustainability Science by the Integrated Research System for Sustainability Science (IR3S) of the University of Tokyo [3]. In both cases, a fast increasing number of papers has been submitted by researchers with different scientific and academic backgrounds.

Based on an integrated and trans-disciplinary approach, Sustainability Science is oriented to study and understand the complexity of the interactions between economy, society and nature in order to propose concrete solutions to complex problems locally and globally threatening the very survival of humanity. Sustainability Science can help in creating methods and visions for analyzing the trade-offs and develops policy-making support tools to solve the concomitant risks to human well-being and security issues [4].

As pointed out by Clark and Dickson [5], Sustainability Science is not yet a traditional discipline, but rather a vibrant arena that is bringing together scholarships and practice, global and local perspectives, and various disciplines. It aims to overcome the traditional mono-disciplinary approach, in order to allow us to see phenomena in their entirety and facilitates the identification of integrated solutions.

A characteristic of Sustainability Science, moreover, is its problem-solving perspective. Komiyama and Takeuchi [3] stated that a unique problem to sustainability science is the process of shifting from the stage of phenomena identification and analysis to that of problem-solving. To attain a goal, we must seek a fundamental understanding of the system as well as solutions [6].

Sustainability Science is a new field that tries to understand the fundamental character of interactions between nature and society [7]. Such an understanding must include the interaction of global processes with the economical, political, ecological and social characteristics of particular places and sectors. The regional character of much of what Sustainability Science is trying to explain means that relevant research has to integrate the effects of key processes across the full range of scales from local to global. Combining different ways of knowing and learning, permits different social actors to work in concert. The role of sustainability science is also the distribution of knowledge to society through communication among experts, decision-makers, academics, politicians. The participation of diverse stakeholders in setting and implementing solutions is indispensable, because as science and technology advance, knowledge tends to be centralized; sustainability science tends to involve different expertises.

3. Energy Sustainability Pillars

The issue of sustainability energy must be fitted in the framework of Sustainability Science [4], because for assessing and promoting sustainable energy systems, needs a transdisciplinary integrative comprehensive framework of evaluation to be provided to society, economy, policy decision makers and industry.

It is necessary to establish cooperation among several key energy-related disciplines, namely: environmental sciences, economics, social sciences and political sciences. Each of these disciplines exhibits strong links to energy issue; for instance, economic discipline discusses the incentives market mechanism for Greenhouse gas (GHG) reductions and incentives for the industry to really and openly enter into the sustainability science debate; political science stresses the importance of including the 4th pillar in the Sustainable Development (SD) framework, the policy and institutional pillar, which is fundamental in realizing a sustainable society. Finally, social sciences are very important for taking into consideration the societal readiness and local appropriateness for the introduction of new technologies. In light of this, it is clear why it is important to analyze energy issues in the framework of Sustainability Science; in fact, its transdiciplinary feature permits understanding the linkage between the above-mentioned disciplines and allows a global vision with different points of view.

The outline of Sustainability Energy definition proposed by the *Sustainability of Energy Systems and Mobility Group*, coordinated worldwide by Interuniversity Research Center on Sustainable Development (CIRPS), identifies five pillars for energy sustainability [8]:

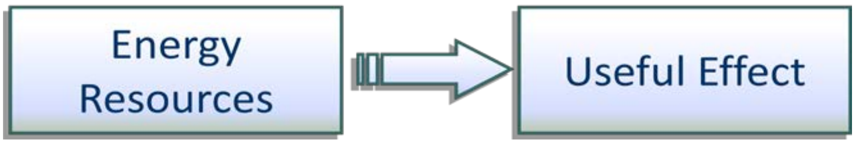
- Renewability of energy resources;
- Efficiency in energy conversion, distribution, use;
- Lowering of environmental impact;
- Increasing of energy accessibility;
- Tailor making of energy systems to meet local social economic-environmental conditions.

4. The Energy Systems in the Age of Energy Vectors

Energy sustainability pillars are the result of many years of study dealing with sustainable energy, renewable resources and energy systems, based on the theory of what we call *closed cycles of energy resources* [9]. The realization of *closed cycles of resources* can be achieved in the energy sector by exploiting renewable resources and structurally integrating energy vectors in the energy system [10].

An energy system uses energy resources to produce a useful effect (Figure 1), that is obtained at the end of the energy chain through a final use of mechanical, thermal, lighting and electric energy.

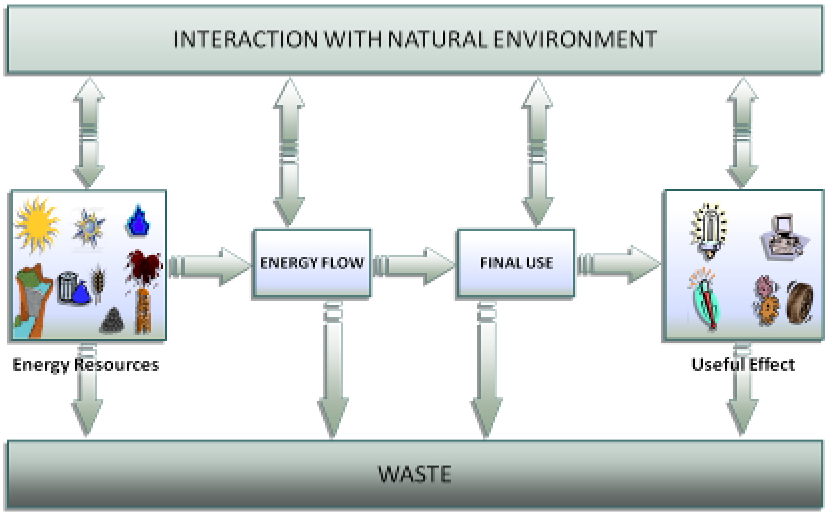
Figure 1. From energy resources to a useful effect.



The energy system must be able to extract energy from the initial resource, to make it flow in the appropriate form and to deliver it with the needed characteristics for the final use that allows the supply of the desired useful effect.

In its most complete representation, we consider an energy system constitutes a set of primary energy resources, processes and technologies for conversion, transport, storage and final uses of energy, waste production and interactions with the environment throughout all phases (Figure 2). To achieve the availability of primary resources everywhere, an energy vector is necessary that allows transfering, in space and in time, a quantity of energy. Therefore energy vectors allow to make energy available for use at a distance of time and space from the resource, intended as the point of availability of the primary resource in nature. The inclusion of energy vectors (to be produced from several primary resources) in the energy system chain becomes a key concept of the entire human development model.

Figure 2. The interaction with natural environment in the passage from energy resources to useful effect.



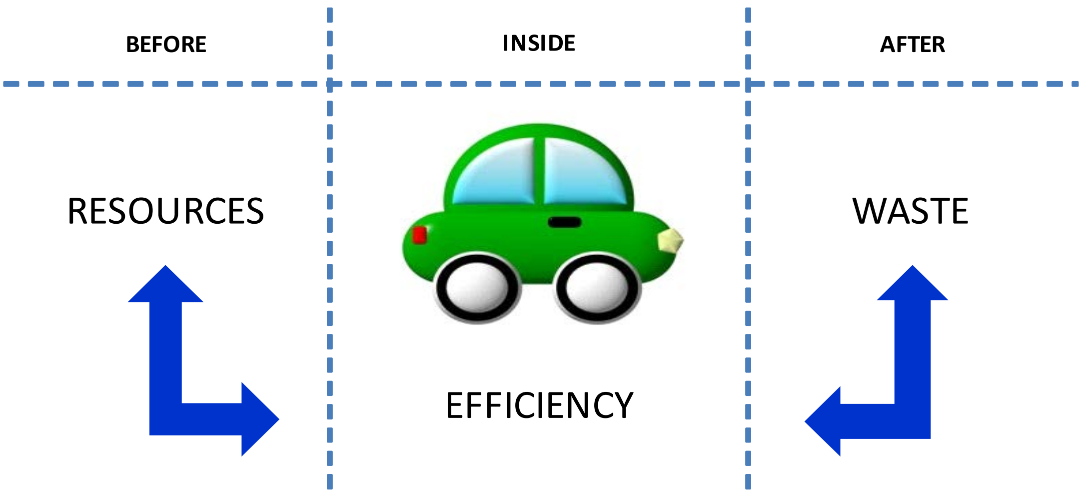
We are moving from the era of petroleum towards the era of energy vectors. Energy systems, including mobility, should be redefined within this new approach. A system using energy resources to produce a useful effect; in the case of energy mobility systems, the useful effect is the mobility of people and goods:

An analysis of a complete energy system (well-to-use analysis), must start from primary resources—considering both the interaction with the environment and any waste products (solid, liquid and gaseous)—to achieve the useful effect [10].

5. The Technology Scenarios for Automotive Sector

An enlightened legislation, that wants to encourage the spread of cleaner cars and contemporarily stimulate a promising development for the energy and automotive manufacturing industries, has to look at the car considering the following three steps in the time-line (Figure 3).

Figure 3. Industries must look at the car with these three steps in the time-line (before, inside and after the car).



5.1. Before the Car

"Before the car" means to pay attention to which resources (fuel or electricity) the energy vectors will use. Factors to be positively considered are:

- The renewability of energy from which the vector is produced (biofuels as bioethanol, biodiesel, biomethane, electricity and hydrogen from renewable resources);
- The manufacturability of the local energy resource, capable of generating employment and entrepreneurship, as well as security and supply;
- Reducing emissions of greenhouse gases (CO_2) and pollutants;
- The accessibility to non-domestic sources of energy needed to feed the vehicles (the availability and reliability of international strategic supply agreements).

5.2. Inside the Car

Looking "inside the car" means to pay attention to the energy efficiency of the system board, summarized in a comprehensive manner by its consumption (CO_2 emissions, in the case of fossil fuels usage). A "path" to increase energy efficiency on board is by the sequential electrification of the car [11]:

- Micro Hybrid Electric Vehicle—Micro HEV;
- Mild Hybrid Electric Vehicle— Mild HEV;
- Full Hybrid Electric Vehicle— Full HEV;
- Plug-in Hybrid Electric Vehicle—PHEV;
- Extended Range Electric Vehicle—EREV;
- Battery Electric Vehicle—BEV;
- Fuel Cell Electric Vehicle—FCEV.

The characteristics of these cars are summarized in the table below.

Table 1. Characteristics of different types of electric cars.

Function System	**Stop & start**	**Electric traction**	**Regenerative braking**	**Electric driving only**	**External battery charge**
Conventional vehicle	Possible	No	No	No	No
Micro HEV	Yes	No	Minimum	No	No
Mild HEV/Medium HEV	Yes	Limited	Yes	Minimum	No
Full HEV	Yes	Yes	Yes	Yes	No
Plug-in HEV (PHEV)	Yes	Yes	Yes	Yes	Yes
Extended Range EV (EREV)	Yes	Yes	Yes	Yes	Yes
Battery Electric Vehicle (BEV)	Yes	Yes	Yes	Yes	Yes
Fuel Cell Electric Vehicles (FCEV)	Yes	Yes	Yes	Yes	Yes (electric and/or hydrogen refuelling)

In this *path*, in addition to hybrid vehicles, electric cars are now ready for the market. And, with a look into the (near) future, the vast perspective of diffusion of electric vehicles, may lead to a revival of fuel cells powered by hydrogen (on-board technology for the production of electricity) as one of the possible solutions for electric car in the coming years. Also hydrogen is an energy vector that can be produced from different resources, so the same goes for everything said regarding electricity.

5.3. After the Car

Looking "after the car" means to pay attention to the pollutants in the exhaust. In this case, attention is now focused on the feasibility of zero emissions at the exhaust:

- Zero emissions for stretches very limited (*Mild* Hybrid Car);
- Zero emissions for stretches limited (*Full* Hybrid Car);
- Zero emissions for urban driven cycle (PHEV plug-in hybrid cars);
- Zero emissions for daily urban driven cycle (BEV, EREV, FCEV electric cars);
- Zero emissions for daily interurban driven cycle (FCEV).

6. Characteristics of Electric Vehicles

Different types of cleaner vehicles, such as electric, hybrid, hydrogen vehicles, exist in the automotive sector, but in our work we focus on the characteristics of electric vehicles, with the aim to show the potential and future benefits, which could be expanded to cover all kinds of cleaner vehicles.

6.1. Potential and Future Benefits

The expected inherent benefits of the product seem to be very distant from those in the current electric cars and will be good for society and the environment; benefiting:

- The purchaser/user;
- The economy of use;
- The current generation.

Many of the immediate benefits identified are not intrinsic, but only potential. They are linked to the occurrence of external conditions being met and not directly dependent on the wishes, or by the conduct, of those who buy and use an electric car, Access to city centers will depend on the individual decisions of municipal authorities.

Even some of the benefits in the short–medium term are not directly controlled by those who buy and use them: first and foremost the cost per kilometer, which is a function of electricity prices set by suppliers and subject to change over time, also in the sense of greater cost, since many of the electric supplies are still tied to the price of fossil fuels.

Even the greatest long term benefit, namely the environmental one, is actually highly dependent on a not very local level, by the mix of sources from which electricity is produced with which you recharge the car. Therefore, especially if the number of electric vehicles becomes significant, it can become completely independent of the buyer's preferences.

6.2. Real and Immediate Benefits

Electric cars have intrinsic and immediate benefits for their users, regardless of the limitations or potential future benefits.

The main immediate and intrinsic benefits of electric cars are:

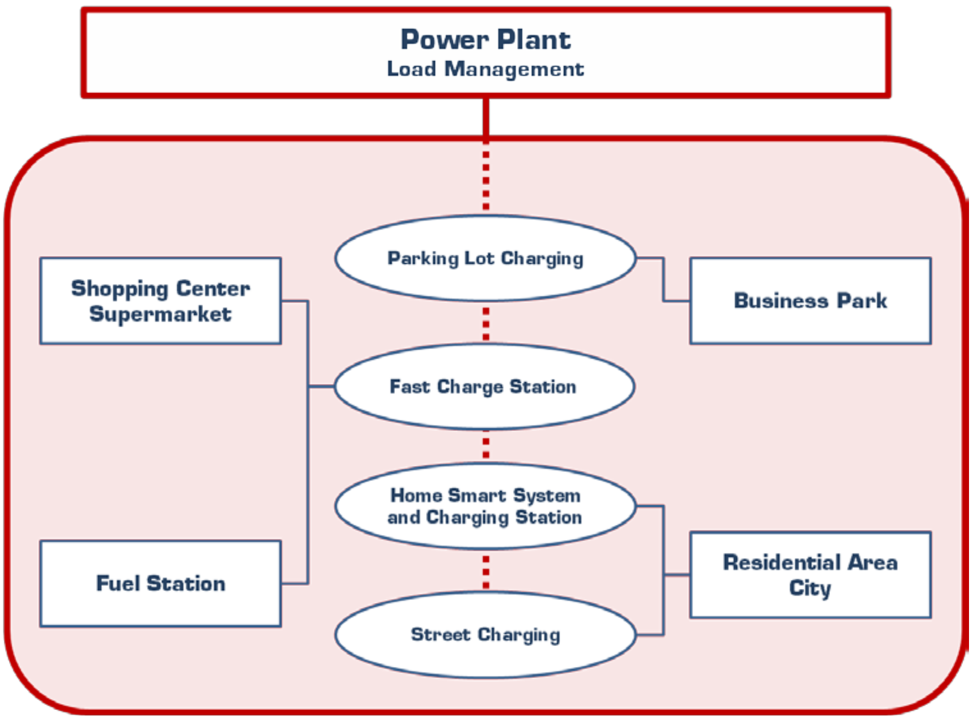
- Self-recharge—possibility of self-recharge directly from their home and at work when the vehicle is not used;
- Self-production—possibility of self-production of electricity for recharging;

The other non-intrinsic benefits of the product but achievable with a specific system of charging are:

- *Renewability of the Resource*—Production of electricity from renewable sources, with guaranteed and long-term lack of emissions in the energy production stage, not only when in use;
- *Reduction of Cost of Use*—Availability of electricity at zero cost, once the cost of the production system has been amortized, thanks to free availability of energy sources depending on the location of the users;
- *V2G Vehicle to Grid*—The so-called smart grids allow advanced power management of recharge of electric vehicles that optimizes and directs energy flows during production, accumulation and consumption.

In an optimized power management, the adoption of V2G infrastructure type is desired. An example of its application is shown in Figure 4 in which a charging infrastructure block diagram for electric vehicles is proposed.

Figure 4. Block diagram example of a Charging Infrastructure.



Considering the large number of potential connections for EVs, in a society in which they have found a strong position, it is immediately perceived how an electrical connection of a vehicle to the network can be understood as a potentially two-way connection.

This means that, when a vehicle is not in use for a longer period, the energy stored in its batteries can be taken from the network and returned (charging batteries) within predefined times to the vehicle user. In short, EV batteries are not only a storage system of “fuel” for electric motors, but also a storage system for electricity to be made available for various final uses.

7. Advice for Policy Makers

Thinking of a possible legislation regarding the energy for mobility, we provide the following comments to contribute to the wealth of information available to the legislator:

- Necessity of appropriate attention to cars with lower environmental impact to provide a legislative framework for the medium to long-term incentive;
- Energy and cars are part of a single system;
- Pay attention to the results in terms of renewability of the primary resource and local (national) manufacturability of energy vector;
- Increased efficiency of conversion on board (reducing consumption and therefore CO_2);
- Consistency of actions with the objective zero exhaust emissions.

Moreover we advise to provide incentives in a “non-homogeneous manner”, e.g.,:

- *Use of energy vectors to be produced by no-oil resource and with CO_2 low emissions (electricity, biofuels, natural gas, LPG)*;
- *Use of renewable energy resources*, because many renewable resources are available on their territory, their exploitation will stimulate local economic development;
- *Small size self-production*, in fact, the possibility of a widespread production of energy vectors with CO_2 low emissions (electricity, biofuels, potentially hydrogen) increases the capacity of the national energy park;
- *Infrastructure*—The new generation infrastructures for refueling/recharging of vehicles with energy vectors at CO_2 low emissions (electricity, but also natural gas / biomethane and hydrogen in the future) must be developed in parallel with an intelligent network for monitoring them and for system optimization;
- *Energy efficiency on board*, which can be summed up as CO_2 systems powered by fossil fuels, allowing competition between different systems by looking at the final result and not at the technology used;
- *Autonomy in low emission mode* (ZEV). Desirable introduction of incentives for autonomy in ZEV mode (up to 5 kilometers; up to 50 kilometers; to 300 kilometers; beyond the 300 kilometers), capable of stimulating competition and technological innovation for zero emissions.

8. Conclusions

To achieve effective legislation regarding the topic of sustainable energy for mobility, we have to start by considering that vehicles and energy are part of the same system. So the legislator, deciding on automotive policies for cleaner vehicles, must consider the entire energy cycle. We offer some advice to policy makers on energy vectors with no-oil resource and with CO_2 low emissions, use of renewable resources direct to a small size self-production, development of intelligent network (smart grid), improvement of the energy efficiency on board, provision of incentives for different ranges in ZEV mode, *etc*.

It is not enough to provide incentives for cleaner cars if a country has not changed the system of energy production, the resources utilized, the production of energy vectors, and the infrastructures.

To achieve an effective change in country policies on energy issues, it is necessary to implement it within a broader framework, which is why we start with sustainability science.

Moving toward sustainability requires revamping the entire system, from the infrastructure to the production of energy.

Conflict of Interest

The authors declare no conflict of interest.

References and Notes

1. *National Research Council Policy Division Board on Sustainable Development, Our Common Journey: A transition Toward Sustainability*; National Academies Press: Washington, DC, USA, 1999.
2. Clark, W.C. Sustainability science: A room of its own. *Proc. Nat. Acad. Sci. U. S. A.* **2007**, *104*, 1737-1738.
3. Komiyama, H.; Takeuchi, K. Sustainability science: Building a new discipline. *Sustain. Sci.* **2006**, *1*, 1-6.
4. Orecchini, F. Energ. sustainability in the framework of sustainability science. In *Proceedings of the International Conference on Sustainability: Resources Circulation and Low Carbon Society*, Osaka, Japan, 22–23 July 2009.
5. Clark, W.C.; Dickson, N.M. Sustainability Science: The Emerging Research Program. *Proc. Natl. Acad. Sci. USA* **2003**, *100*, 8059-8061.
6. Kajikawa, Y. Research core and framework of sustainability science. *Sustain. Sci.* **2008**, *3*, 215-239.
7. Kates, R.W.; Clark, W.C.; Corell, R.; Hall, J.M.; Jaeger, C.C.; Lowe, I.; McCarthy, J.J.; Schellnhuber, H.J.; Bolin, B.; Dickson, N.M.; *et al*. Environment and development: Sustainability science. *Science* **2001**, *292*, 641-642.
8. Orecchini, F. Energ. sustainability pillars. *Int. J. Hydrog. Energ.* **2011**, *36*, 7748-7749.
9. Orecchini, F. The era of Energ. vectors. *Int. J. Hydrog. Energ.* **2006**, *31*, 1951-1954.
10. Orecchini, F.; Naso, V. *Energy Systems in the Era of Energy Vectors—A Key to Define, Analyze and Design Energy Systems Beyond Fossil Fuels*, 1st ed.; Springer: London, UK, 2011; Volume 354, p. 176.

11. Orecchini, F.; Santiangeli, A. Electric and hybrid vehicles—Power sources, models, sustainability, infrastructure and market. In *Automakers' Powertrain Options for Hybrid and Electric Vehicles*; Pistoia, G., Ed.; Elsevier: Amsterdam, the Netherlands, 2010; Chapter 22.