The hidden face of efficiency

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Abstract

Efficiency has a double face: it is necessary, but sometime it is an illusion. It is not the solution for an energy hungry world, but is a part of the solution for a sustainable world. Exploring the boundaries of efficiency is like to be inside the smallest box of a Chinese boxes set; If you don't open your mind to the world outside, you will stop to the walls of the smallest box thinking to have done the best possible, ignoring the largest scenarios to be explored. In this article are described the different approaches to explore the infinite efficiency scenarios that can be opened in the future. Efficiency could be an as costly as useless exercise, with the only effect to move a little bit on the limit of an economic system that is overexploiting natural resources and damaging the ecosystem services fundamental for life. To avoid it is necessary to drive investments to create an efficient economic and human environment, building specific infrastructures, like smart grids, and heat pipes, promoting energy exchanges among different end uses. In other words, before promote efficient appliances on the consumerist market, it is necessary to define a pattern of sufficiency to create a new efficient scenario of a qualitative wellbeing looking forward to a circular and sustainable economy.

1. Introduction

Among the several "evolutionary pathways" that a living system can cover in its history, the one that prevails is always that which is able to preserve the greatest quantity of energy and matter made available by the ecosystem in which it belongs, "transforming it in organisation." Thus, there is an evolution from disorder towards order that involves in a coordinated way all the living systems belonging to a certain ecosystem, and tends towards the maximum efficiency of available resources exploitation.

If we extend such remarks to the whole planet, we can say that the evolutionary history of the Earth is a walk towards higher levels of organisational complexity that keep it progressively farther away – from equilibrium of maximum entropy, from every possible exhaustion of difference, from the end of life, from the end of existence in the homogeneity of absolute disorder.

We have seen that the world tends spontaneously to annihilate all differences and consequently to exhaust all possible transformations. But some parts of the world, those we call living parts, seem to take the opposite direction, seem to invert time direction marked by the process of differences reduction. Living systems tend to improve their capability for storing energy and to increase their distance from equilibrium with the outside environment, namely to increase differences. They do it mainly in two ways:

1. Quantitative: increasing the physical dimensions and consequently the flow of captured solar energy; this allows a higher capture of the incident solar radiation, but this implies also a higher energy of maintenance.
2. Qualitative: improving its organisational complexity so that the received solar energy and materials can circulate for a longer time inside the system.

The second way implies an increase of the genetic information and thus of complexity. The system (organism or ecosystem) tends to become energetically more efficient and normally carries more information (the organism doing so with a more complex genetic code). Biodiversity increases. The number and the specialisation of ecological niches increase. Overall, information, namely that of genetic and biochemical complexity, increases. We can say that if a system is crossed by a continuous flow of energy, it moves away from thermodynamic equilibrium and selects the components and the organisation that brings to it the higher flow of useful energy through the system and thus to the storage of the highest possible quantity of energy in the form of organisation.

The outcome is a system where the entropy increase is minimal because, while the system evolves, the speed of growth of stored energy is higher than the energy lost. This leads to an increase of the potentiality of the success in evolution of the system, which is called "ascendancy" (Ulanowicz 1997). The higher the ascendancy, the greater the ability of the system to respond to external perturbations, gaining a further progress in evolution in terms of efficiency.

The evolutionary aim of efficiency emerges at every scale level in this thermodynamic interpretation, from the single unicellular microorganism to the most complex systems, from the Earth to the entire universe (Masullo 2013).

The growth of efficiency in natural systems has no limits because they grow in quality by the model of circular economy. Human linear economy growing in quantity and efficiency is only one way to move the limits of growth slightly into the future.

When we talk about efficiency related to human economy, we assume that it is in any case a positive issue; but this is not always true. We can find many examples in which the most negative purpose is pursued with the highest efficiency. There is nothing worse than going with the highest degree of efficiency in the wrong direction. To consider efficiency as truly positive we have to be sure to proceed in the right direction. For example, to cut 50% of greenhouse gases by 2050, it is not sufficient to improve efficiency by 50% if we accept that, with the trend of growth of the last 40 years, energy consumption will double. Our economic system is based on a continuous growth of the Gross Domestic Product (GDP); it can be pursued essentially in two ways:

1. The growth of per capita demand of goods;
2. The growth of population.

Economists suggest following both ways in concert, with both resulting in an increase of energy consumption. According to *2013 Key World Energy Statistics*, published by the International Energy Agency, in 2011 the world Total Primary Energy Supply (TPES) amounted to 13,113 Mtoe[1]; for a population of 6,958 million this results in a TPES per capita of 1.88 toe. But we have to consider the inequality of supply: for the OECD countries[2] the TPES was 4.28 toe/capita; for China it was 2.03 toe/capita; for Africa it was 0.67 toe/capita. Assuming that a worldwide 2.00 toe/capita could be a good target for an equal and sustainable world in 2050, people living in an OECD area must halve their per capita supply, while China must maintain it stably, India must grow from 0.60 toe/capita and Nigeria from 0.73 toe/capita. Unfortunately, India, China, and Nigeria will be the three most populous countries in 2050, with 1.652 billion people, 1.314 billion people, and 440 million people, respectively. And China is looking forward to reaching the OECD model of consumption as their target.
Nevertheless, supposing to reach this ambitious world target of 2.00 toe/capita, in 2050 we will need to provide for the 10 billion people populating the world with a total primary energy supply amounting to 20,000 Mtoe. During the thirty-nine years from 2011 to 2050 we would need to deliver to the world population 563,901 Mtoe. To have an idea of the dimensions of this challenge, consider that the global reserves of the principal fossil fuels, oil, coal and natural gas, amount to 1,025,180 Mtoe[3]. Therefore, in this scenario in 2050 we will have exploited 55% of the global reserves of fossil energy known today. This shows on the one hand the dramatic importance of efficiency and on the other hand its insufficiency and of the ultimate necessity to redefine efficiency.
Furthermore, in the affluent part of the world – which in our scenario needs to halve its energy consumption – another uncertainty can obliterate the gains made on efficiency: individual behaviour.
A study made in 2002 by E.C. Alfredsson for the Swedish Institute of Growth Policy Studies (ITPS)[4] posited that there are many doubts that changes in the patterns of consumption could produce effective benefits in energy and CO_2 reduction. By switching to "green consumption", energy use and CO_2 emissions can only be reduced in the short term, but in the long term this will increase at the same rate of economy. Alfredsson considered changes in food consumption, in transportation and in housing. This means that if we don't change the structure of an economy based on growth, every effort spent on efficiency will be ineffective: efficiency without sufficiency does not make a large difference. If we don't reduce the level of consumption, efficiency risks only being a short-term palliative (Alfredsson 2003).
The challenge is the transition from an "energy-hungry world" to a "sustainable world". In other words, energy efficiency could be a strategy to contain the negative effect of an *energy-hungry* world during the transition to a *steady state economy*. Efficiency that is effective for CO_2 emissions reduction must be applied not only at the energy end-use level, but to all of the economic system, trickling down in the energy chain to the end-use.

2. Exploring the limits of efficiency: a problem of scale

Usually, when we want to improve efficiency, we consider durable goods (i.e. refrigerators, freezers, air conditioners, washing machines, domestic lighting, ICT equipment) and review the market leaders. Finally, we choose the most suitable within our budget (figure 1a). This is the Best Available Technology (BAT) approach. If we use only this criterion we risk making a big mistake: falling into the wrong use of the right criterion. For example, if we want to improve efficiency in our heating, ventilating, and air-conditioning (HVAC), we consult a catalogue for heating/cooling device prices and performance. We are enthusiastic while exploring the first part of the graph in figure 1a, where a slow growth of cost corresponds to a fast growth in efficiency. When we arrive at the dotted line of the graph we stop because any little growth of efficiency corresponds to a high growth in cost; so we believe we have reached the top of an economically consistent efficiency.
The same thing occurs if we desire to be more efficient in transportation. Most people think that the solution is to simply buy a new car. Also, in this case we will stop at a point where we believe we have reached the best we can on an individual scale.
But this is absolutely not the peak of efficiency. We can envis-

1. Mtoe means millions of tons of oil equivalent.

2. Industrialised countries that are members of the Organisation for Economic Co-operation and Development.

3. Calculated from data reported in the WEC 2013 report, using standard conversion factors.

4. Swedish Institute of Growth Policy Studies (ITPS), Student plan 3, SE-831 40 Östersund, Sweden.

age a new scenario, as in figure 1b.
In the case of household air-conditioning requirements, if we change the scale of our analysis and shift our attention from the device itself to building performance, we enter a new scenario of efficiency to explore with much more pos-

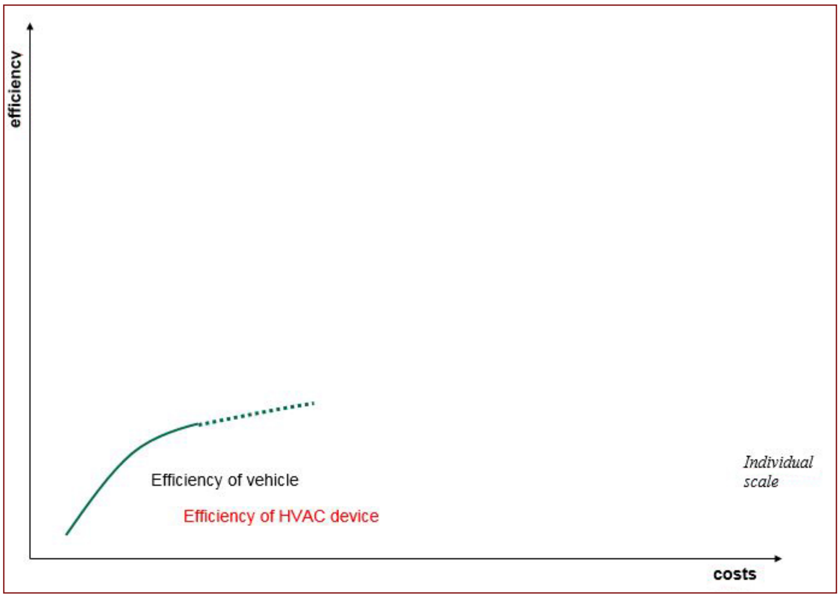

Figure 1a – The best available technologies.

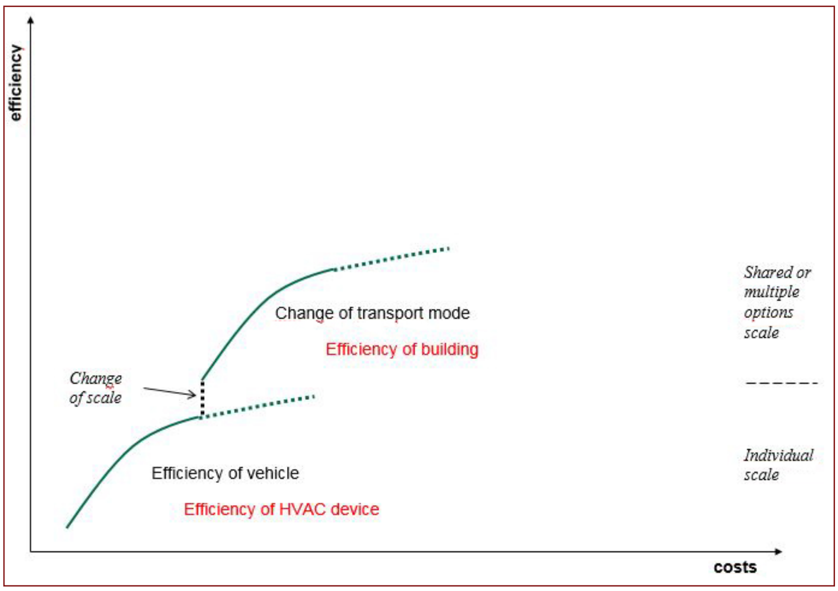

Figure 1b – Optimised energy service.

sibilities to consider: we have entered a shared or multiple-option scenario. We can insulate windows and walls, change the heating and cooling distribution system, introduce a passive system as shading or as a solar air heater, improve air circulation, and so on. In the case of transportation, we can choose among different transportation modes available, having many more possibilities to consider, and with different combinations of more than one mode; in other words we may explore the possibilities of an intermodal solution. Also in this case, where the slope of the graph declines we reach a point that we consider most consistent with our budget. But again we can open a new scenario (figure 1c) on an urban or district scale.

For the household air-conditioning requirement we can drive our attention to an integrated energy system such as a micro-tri-generator that uses a geothermal heat pump, to solar energy, or to implementation of a local smart grid for a group of buildings or for the entire city. In this case it is possible that the device considered in our first step would not actually be needed, or that its dimensions could be much smaller. For transportation we can consider how much our transportation requirement is due to a poorly organised life, or to an inefficient organisation and distribution of social, cultural, sanitary, administrative services, etc., or to a lack of transportation services offered by the local administration; therefore we can basically reconsider our transportation requirement.

The uppermost step is to think on a national or international scale (figure 1d) and consider the efficiency of the entire chain, from primary to secondary energy commodities (IEA 2005). Primary energy is that extracted or captured directly from nature. In any case we use technologies to extract it – drills to extract oil and gas, solar panels to extract heat from solar radiation, photovoltaic devices to convert solar light to electricity. In the case of oil, methane, or coal extraction, we consider efficiency as the ratio between energy return and energy invested (EROEI); this ratio dramatically decreases with the necessity to exploit deeper and deeper gas and oil fields and coal mines despite an increase in efficiency of drilling technologies. The energy invested includes the quota of the energy spent for the production of all machinery used relative to each unit of energy extracted.

For solar heater and photovoltaic devices, efficiency can be defined two different ways. The first way is the ratio between the energy spent to produce the device and the energy collected or converted during its life. The second way is the consideration, in the case of a solar heater, the ratio between the heat transferred to the thermovector fluid (diathermic oil, water, or air) and solar radiation. In the case of photovoltaic we can consider efficiency as the ratio between the electricity produced and solar radiation. Considering the whole spectrum of solar radiation can help us to understand what is the most efficient use of a surface exposed to sunlight: a photovoltaic device or a solar heater.

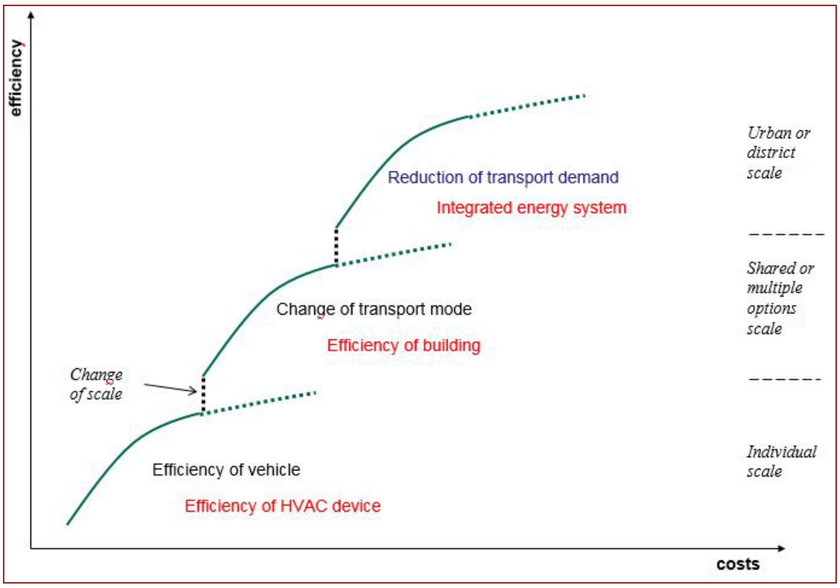

Figure 1c – Optimised system organisation.

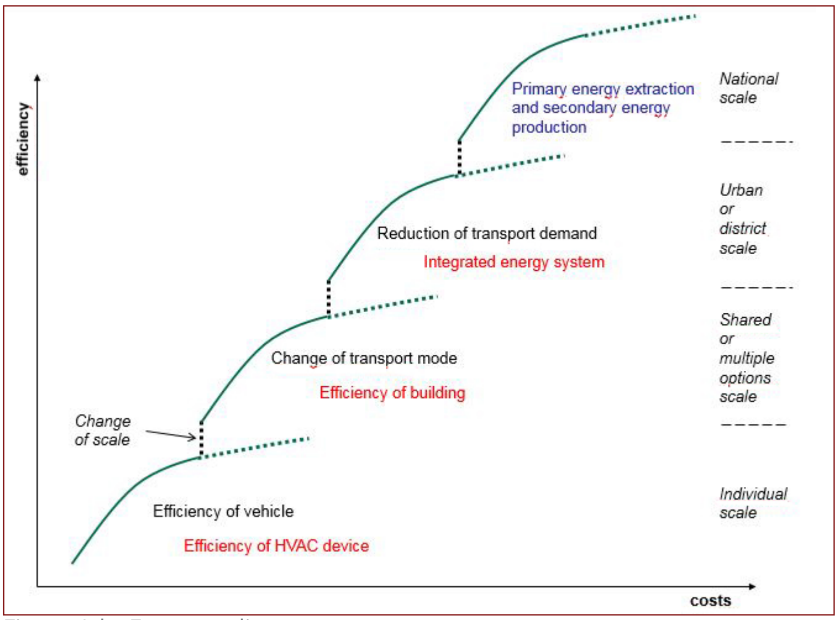

Figure 1d – Energy policy.

Now we have to consider the efficiency of conversion from primary to secondary energy, including in oil refineries and thermoelectric power plants. At the end of the chain we can evaluate the efficiency of the distribution system: pipeline, coal transport, electric grid.
Only at this point is it correct to consider the efficiency of the local supply system and of end uses.

3. What is efficiency from the end-use point of view

At this point we can see that in a systemic approach, efficiency assumes a new light and a new possibility to become strategically effective in reducing CO_2.
We can clear up what is efficiency in a sustainable pattern.
To begin, we will show what happens in a **supply side approach** (figure 2a), the most commonly adopted. The box with the question mark is a generic system that requires energy; you can imagine a house, a building, a city, or an industrial district. Each user asks the utilities/companies to satisfy their energy needs. The company is not interested in which are the final needs of the user: the user is a customer and the need is a demand. It sells the customer the energy requested. This is its business.
The energy supplied flows through the system, producing the desired effect and then is lost in the environment. The only effects we can monitor are the growth of entropy, the environmental impact, and the level of user satisfaction.
To reduce the impact of the system we can adopt an **end-uses approach** (figure 2b), watching inside the box and finding the energy sources that match best the quality requested by each end use. For example, if the system is a house, to produce sanitary water we will use a low-temperature heat source, such as a solar collector. For cooking, we will use a high-temperature heat source such as natural gas, and so on. The result will be a similar quantity of energy lost, but a lesser increase of entropy and probably a lower pollution rate.
The scenario starts to change significantly when we use an **end-uses efficiency approach** (figure 2c), shifting our attention from energy itself to energy services. Our point is no longer to calculate how much heat at low, medium, and high temperatures is needed, or how much electricity, but which are the services I want to obtain by using this energy. For residential, it is needed for light, music, computer use, preservation of food, cleaning clothes and washing dishes, transportation, an agreeable temperature in winter as in summer, etc. For an industrial district, the services needed are power for equipment, light, transportation, process heat, etc. We can save energy using the best available technologies in lighting, washing, air-conditioning, television, computers, and more efficient industrial equipment.
The **system approach** (figure 2d) is the only way to achieve significant and enduring results in terms of energy use and CO_2 emission reduction.
For instance, in the case of an industrial district, energy output of equipment using high-temperature heat can easily be used as energy input for a process that requires low-temperature heat. With a review of the processes implemented

inside the industrial district, we can implement the recycling of materials among the different activities, thereby reducing waste production. Modifying in a proper way the industrial processes, we can optimise the materials and energy exchange inside the system, such as what occurs in an ecosystem. Efficiency in a sustainable pattern means optimising the material and energy flows passing through the system, maintaining for the longest possible time its circulation inside the system to produce the most useful effects before being lost as output. Only after having optimised the system in such a way can we usefully consider the choice of the more efficient appliances and devices as elements of the system. Therefore, we can finally create an **intelligent integrated system** (figure 3) able to produce multiple services. The integration of the largest available pattern of renewable resources will open new markets for renewable energy, avoiding problems related to each single technology (low intensity, intermittence, etc.) and giving to the customer the most flexible, reliable, economically and environmentally efficient system. As in computer science, which matured when the sector switched from hardware to software, the same will happen with energy. It is the same as occurs in biology when a system evolves from a poor state (a quarry) to a very high-level state (a tropical forest) by an enrichment of biodiversity. In a sustainable system, the role of biodiversity is covered by the *technological diversity* that ensures a high resilience to the system, making it able to adapt to variations of conditions, just as in the sources in the market of technologies and sources (Jackson 2009).

4. Energy efficiency in the economy

In national reporting, the efficiency of the energy intensity of GDP is often considered. This is very misleading; it brings us to say that a country whose economy is based on tourism is more efficient than one whose economy is based on, for example, the steel industry, without evaluating the efficiency of hotels, restaurants, the transportation system, and all the other services and activities related to tourism. Energy intensity of GDP could be useful if a country is ready to transform deeply its economy, phasing out the most

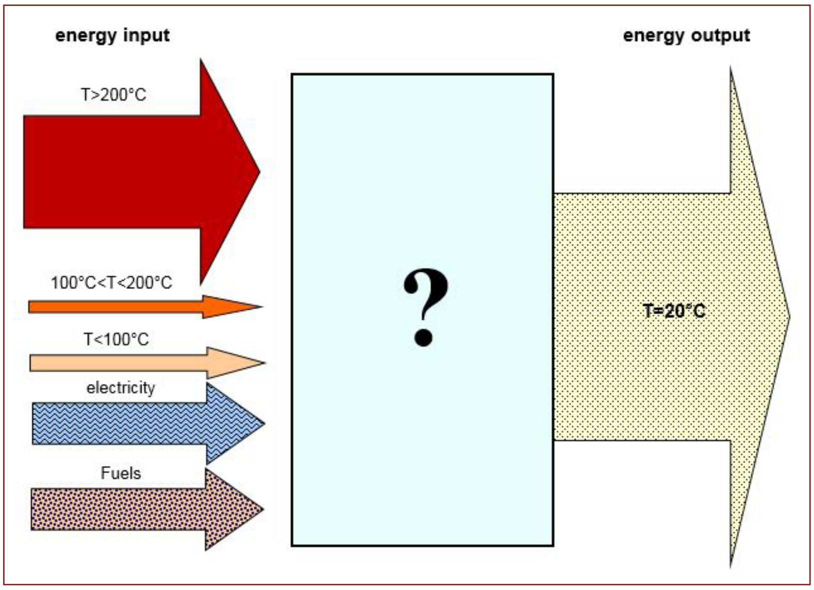

Figure 2a – Supply side approach.

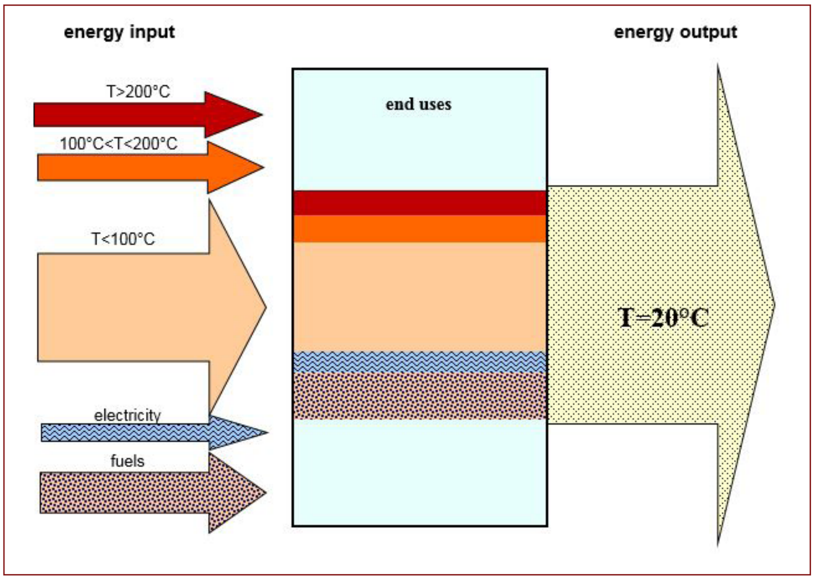

Figure 2b – End-uses approach.

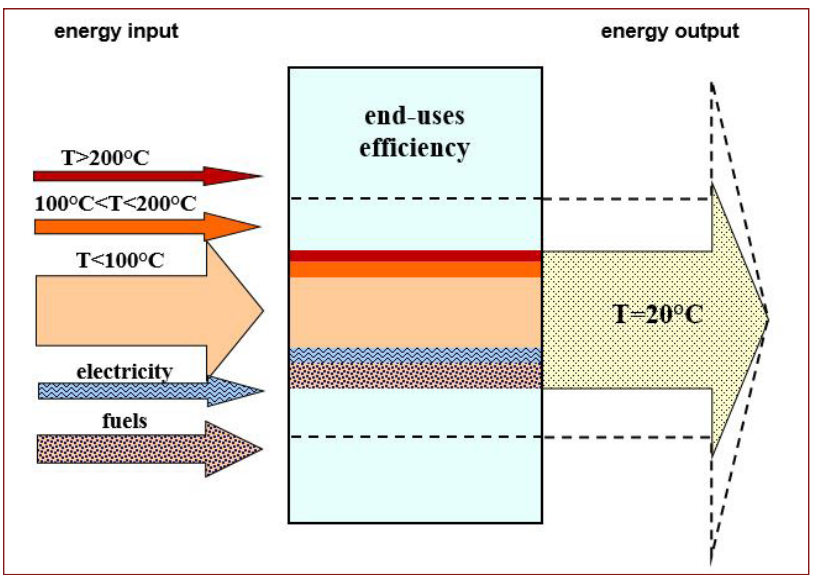

Figure 2c – End-uses efficiency approach.

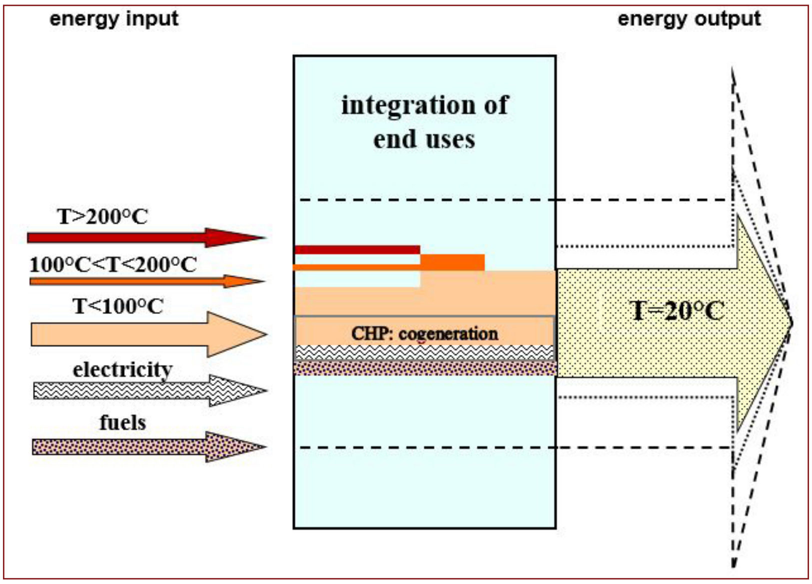

Figure 2d – System approach.

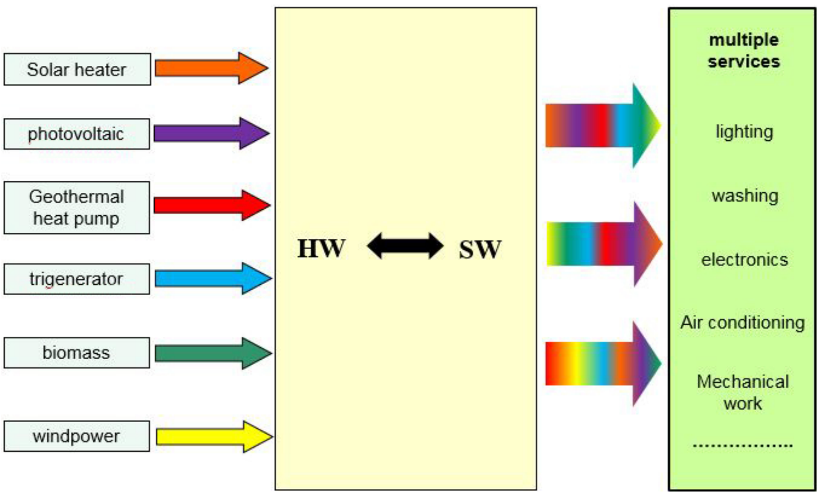

Figure 3 – Intelligent integrated system.

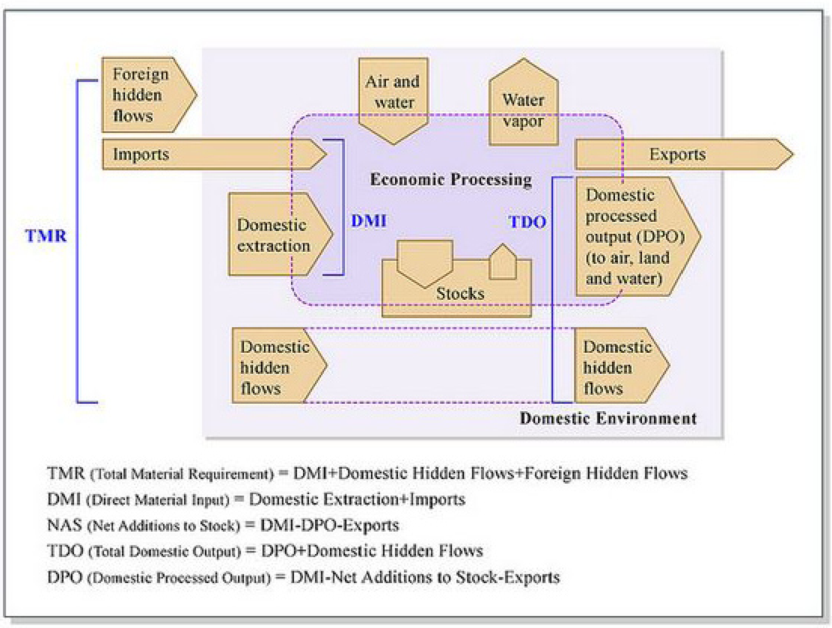

Figure 4 – Material flow (WRI–The Weight of Nations).

energy-intensive activity. Income and GDP are not parameters in which is found the definition of efficiency. For the economy, efficiency is converting the greatest quantity of natural resources in value in the shortest time. It implies the production of the greatest quantity of goods that have the shortest durability acceptable by consumers. It is the opposite of the definition of scientifically based efficiency.

Another component of economy efficiency, and one which is often inopportunely disregarded, is the energy flow that crosses the economic system, embodied in goods and materials, including the hidden flow related to extraction and production activities that are implemented outside national boundaries (see figure 4). This depends on the organisation of the national market and the industrial system and can allow us to have an exhaustive balance of energy used, directly and indirectly, to feed the national economy. Efficiency in this case is the sum of energy used in each branch of the economy, compared to the best available technologies. All the inputs related to each activity could be evaluated using an input/output matrix like that in figure 5. It is formed by the following submatrices and vectors:

Matrix A: contains goods input to each sector.

Matrix B: contains goods output from each sector.

Matrix C: contains the primary input to each sector.

Matrix D: reports how much of each good is requested to satisfy final demand.

Matrix E: reports how much primary inputs are requested to satisfy final demand.

Vector F: reports the total demand of goods from sectors and final demand.

Vector G: contains the total outputs for each sector.

Vector H: contains the total primary inputs.

Vector J: contains the total expenditures for all goods and all primary inputs.

Vector K: represents the total output of goods.

Vector L: represents total inputs to sectors.

Vector M: represents total inputs supplied to satisfy final demand.

Matrix N: contains the quantity of wastes disposed in ground, water and air to satisfy the final total demand of goods represented by matrix F.

Matrix O: contains the quantity of wastes produced by each sector and disposed in the environment.

Matrix P: contains the total amount of waste output from the economic system.

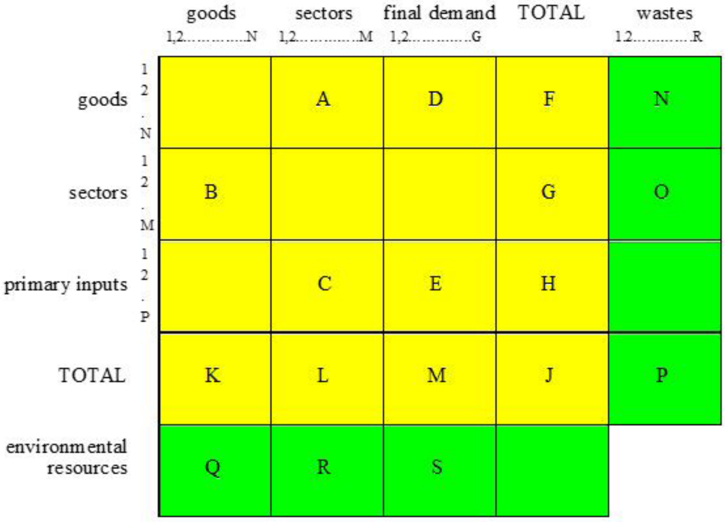

Figure 5 – INPUT/OUTPUT matrix.

Matrix Q: contains the input of natural resources requested to produce each type of good.
Matrix R: contains the input of natural resources requested by each sector.
Matrix S: contains the total input of natural resources to satisfy final demand.
If we substitute in each voice of this matrix the energy embodied in weight for quantities, our matrix will describe the energy flow throughout the economic system.
We can produce two matrices: one representing the real input/output of the economy, and the other one filled with energy data related to the best available technologies, representing a sort of best reference. Comparing the two matrices, we will consider the range between them as representing the efficiency of the economic system.

5. A case study: light and shade in the Italian Efficiency National Action Plan (PAEE)

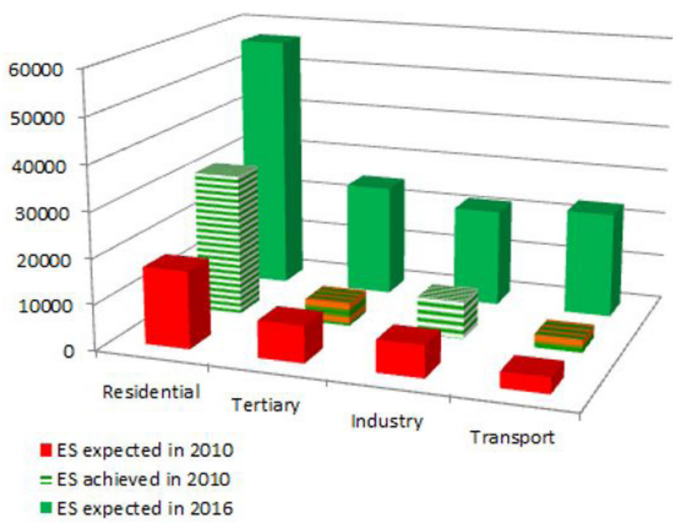

Figure 6 – Annual energy saving (ES) - source PAE 2011 (GWh/y).

The first PAEE was presented in July 2007 to implement European Commission Directive 32/2006. The plan was updated in July 2011 according to the 2020 European target of -20%. The plan fixes targets for 2016 for the residential, tertiary, transportation, and industrial sectors. The intermediate targets of 2010 have been over passed by about 50% in the residential sector, while those of the tertiary reached only 8% of target, industry 47%, and the transportation sector 85%. It is interesting to look at the details of these results.
In the residential sector, big success resulted in the type of actions that have an immediate and durable effect on important aspects of the family budget, such as insulation of walls and windows and replacement of inefficient heating plants with more efficient ones reaching, respectively, 156% and 171% of target. Less attractive seems to be the substitution of washing machines for market presence of less efficient appliances at a lower cost. In this case, less than 8% of target has been reached. But the target would seem less difficult if we were to put a lower limit to the efficiency of marketable products, as has been done in phasing out incandescent light bulbs; in this last case the success is evident: the result was more than double the target.
The evident failure of action proposed to the tertiary sector is probably due to the fact that the price of services is less dependent on energy and goods as on commercial activity, and in many cases the cost is covered by public administration, which usually pays less attention to the less important component of final costs. In this case it is important to induce or to force more responsibility of the actors on environmental grounds.
Particular attention needs to be paid to the failure of the plan in the industrial sector, where less than half of the target was reached. Regarding the substitution of electric engines with more efficient ones, only 1.5% of the action target was achieved. The revamping of machines in this sector failed completely while the use of high efficiency combined heat and power (CHP) systems enjoyed great success. Industries seem to be interested in improving efficiency in their energy self-production but not in a better end use. Probably, this is due to the prevalence in the Italian industrial system of small- and medium-size industries and manufacturers (SMEs) that are reluctant to make important investments in machinery dedicated to specific operations in the industrial process without long-term certainties regarding economic and market scenarios. In this, case the solution could be to support and promote the cooperation of more enterprises to implement efficient common-energy services, leaving more capital available for specific single actions (Bertini et alii 2011).

6. The importance of a network initiative

Some actions are required to implement energy efficiency in a sustainable pattern, according to the three levels below:

- Politics;
- Education/information;
- Direct action.

Actions must have a synergistic effect to stimulate a network initiative. They must produce interchangeable results and experiences and must be so flexible as to be adaptable in different contexts.

Politics

1. Introducing in national legislation a law that submits to an *Energy Efficiency Assessment* (EEA) any activity or project that implies a significant energy use related to the energy services the project wants to provide. The EEA must be determinant for authorisations, licenses, and public financing.
   For instance, the EEA for a transportation infrastructure project must be evaluated with an energy analysis of both the construction phase and of the transportation service offered. The evaluation must be comparative with other possible solutions (motorway, railway, maritime transport...).
2. Substituting plans for new, conventional high-power plant construction with plans for integrated local networks of renewable energy plants connected to smart grids.
3. Implementing of national and local energy plans oriented to local generation in integrated smart grids promoting energy efficiency both in the energy supply and demand chains. The plans must include enhanced energy performance requirements for appliances. The plans must contain a strategy for phasing out the most inefficient appliances and devices.
4. Establishing financial support for the creation of smart industrial districts.
5. Linking of licensing for building up industrial, commercial, or housing projects in respect to high-efficiency standards.

More of the actions listed above have been considered in recent legislation that implements the EU directive on energy efficiency, but there is still a lack of a systemic pattern that organises such actions into a hierarchy that also includes the synergies among them.

Education/information

1. Initiatives to introduce into educational programs the basic concept of efficiency
2. Information campaign to promote efficient solutions such as LED lighting, sustainable mobility, efficient vehicles, efficient buildings
3. Green-point creation in shopping centres to deliver information about efficient solutions
4. Agreements with public and private partners to spread market information on the availability of efficient solutions.

Also, the actions listed above have been introduced into plans and financial initiatives supported by local and national administrations, although the actions implemented are sporadic and fragmented and not producing an economic scenario for the future.

Direct actions

1. Promote the constitution of citizens' trusts and commonwealths, or popular shared companies to develop the project of a local integrated efficient system
2. Promote projects of energy "independence" for communities.
3. Promote the constitution of zero-emission communities.
4. Form citizen networks for diffusion of zero-emission solutions.
5. Form legal initiative to oppose project inefficiency and installation of coal-fired and nuclear power plants.

7. Conclusions

Efficiency is not an objective value but, if scientifically based, is actually a subjective value. The importance of pursuing efficiency depends on the purpose we have based it on. It can imply both quantitative and qualitative evaluations. If we define the efficiency of a killer as the number of bullets he needs to shoot to kill his victim, it is better to be inefficient. If we define the efficiency of an ice cream maker as the number of ice creams per hour he can produce, maybe it is better to change ice cream parlours! But anyway it would be fair to ask the ice cream maker to use a high-efficiency class refrigerator.

We can conclude that efficiency has a double face: it is necessary, but sometimes it is an illusion. It is not the solution for an energy-hungry world, but is a part of the solution for a sustainable world. Exploring the boundaries of efficiency is like being inside the smallest box in a set of Chinese boxes; if you don't open your mind to the world outside, you will stop at the walls of the smallest box, thinking to have done the best possible but in fact ignoring the largest scenarios yet to be explored. The different approaches to explore the infinite efficiency scenarios that can be opened in the future are described in this paper. Efficiency, if solely applied, could be a costly exercise insufficient to drive humanity towards a sustainable future, producing as its only effect that of moving a little bit on the limits of an economic system that is overexploiting natural resources and damaging the ecosystem forces fundamental for life. To avoid this, it is necessary to drive investments to create an efficient economic and human environment, building specific infrastructures like smart grids and heat pipes, promoting energy exchanges among different end uses, and recycling materials. In other words, before promoting efficient appliances on the consumer market, it is necessary to define a pattern of sufficiency to create a new efficient scenario of a qualitative wellbeing looking forward to a circular and sustainable economy. In this sense, efficiency is much more than operating a machine with the lowest energy supply, but it is how to produce the highest wellbeing using the lowest amount of resources.

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