THE USE OF MATERIALS, SPACE AND ENERGY FROM AN EXERGETIC PERSPECTIVE

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Abstract

The increased use of sustainable energy has led to increased demands for physical space since most sustainable energy generation is directly or indirectly linked to solar energy and a corresponding solar 'catchment area'. Thus, energy generation now increasingly has to compete with other forms of land use.

As part of the SenterNovem research program "synergy between regional planning and exergy" (SREX) a research project has been set up, titled "exergetic systems analysis on a regional scale". In this project the relation between space, energy and material resources from an exergetic perspective is investigated with the aim to derive principles to aid decision making in spatial design.

In this paper it is concluded that biodiversity is an important marker for the quality of space and life. According to the second law of thermodynamics it is also concluded that the use of material resources inevitably results in entropy increase (exergy-losses) which can be compensated by expending energy. Thus, the use of material resources can be expressed in terms of exergy. Almost all the exergy on earth comes from the sun and because there is an upper limit to the amount of available solar energy on earth this also constrains energy and material use because of the limited earthsurface. The way in which this limited space is used for energy and resources, has consequences for the biodiversity. Thus we can use biodiversity as a measure of environmental impact of spatial plans.

The impact of the use of energy, space and material resources on biodiversity, makes their efficient and effective use important. The principles of upcycling and downcycling can be applied in spatial design to make more effective use of our resources and space. Thus we can reduce our primary energy use and the use of space for human consumption, without losing biodiversity. It is important to address the scarcity of physical space, material resources and energy thoroughly and thoughtfully to optimise systems that provide for the demands of our modern society. This understanding is a valuable premise for making decisions regarding spatial planning and sustainability, and a necessary basis for the development of a design principles.

1. Materials, energy and the use of exergy

Sustainable building policy currently focuses on reducing energy use in buildings. New buildings in The Netherlands have to conform to energy-performance conditions prescribed in the building code, while existing buildings are given an energy-performance label (much like refrigerators and other electrical household appliances) derived from the Energy Performance of Building Directive (EPBD). While energy use in buildings is a current issue, there is more to sustainable building. There are plans to incorporate in the Dutch building code, not only energy performance but also aspects related to material performance and even water performance. The material performance conditions may be even more important to sustainability than the energy performance aspects [1]. After all, the sun is for all practical purposes a constant and abundant source of energy, while the material resources on earth are finite. Materials are being used in the sense that they are being mixed, in a chemical and physical sense, and after use and possibly re-use, eventually all end up in the refuse-tip.

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For instance, the production of the current generation of photovoltaic (PV) cells with which we convert solar radiation to electrical energy, requires a lot of material resources and energy. Life cycle analysis (LCA) of a

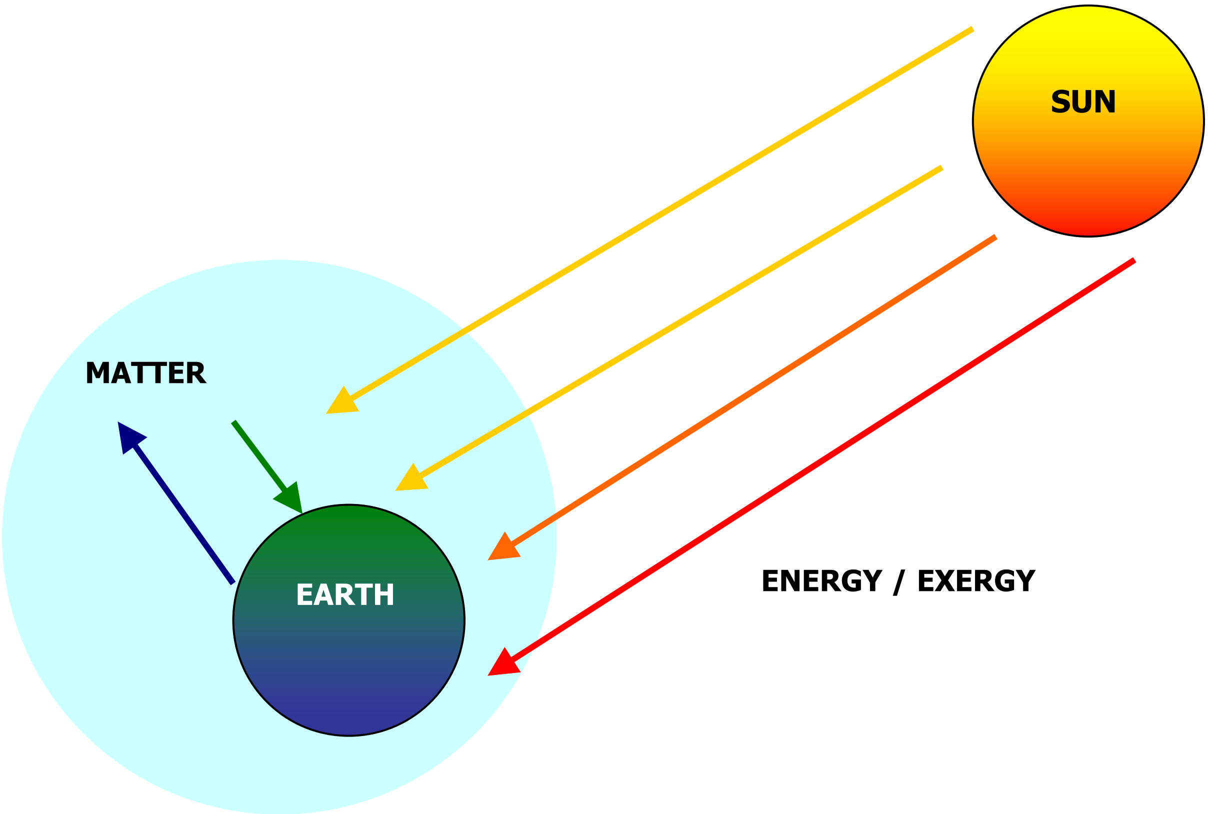

Figure 1: Matter is not increasing on our earth, only energy from the sun is. (Leo Gommans –TUDelft)

PV-cell indicates that, depending on the type, it must operate in optimal conditions for about 5 years to generate the energy it took to produce it, i.e. to pay back its energy costs. After approx. 20 years, a PV-cell will end up in the refuse tip. At the best it will be re-used, in parts, for a lower-quality purpose. The extent of re-use will depend on the availability of technologies to separate useful components. Even if re-cycling PV-cells for high-quality purposes is possible, this will require energy. In theory, the energy-use for this so-called “upcycling” [1] should be included in the determination of the environmental impact of PV-cells (or other material resources). Inevitably, the energetic pay-back time of a PV-cell increases substantially when the cost of upcycling is incorporated. An interesting aspect of the cradle-to-cradle approach in which upcycling costs are accounted for, is that material use can, in theory, be expressed in an amount of energy (or better, exergy). This equivalence is an important step towards the development of a design-tool, because the environmental impact of material and energy use, till now, has been expressed in separate measures, which are not comparable.

2. Cradle-to-cradle in building construction practice

The interesting thing about the cradle tot cradle approach is the fact that Braungart and McDonough include the upcycle principle in the Life Cycle Analyses [1]. This forces us to think about our design product, after it is used: how our waste can become food (feed stock) again. For most of the materials we use today for our design products, it is not always possible to reuse them as a high quality resource. Either it costs a prohibitively large amount of energy or we simply don’t have the adequate technology for it. For this reason most of the materials are not reused and finally end in the refuse tip or in an incineration plant, which mostly make them even more unusable for high quality purposes.

Since we are not familiar with this cradle-to cradle approach and the endless reuse of materials using only energy, there is almost no generic data available on how much energy is needed for upcycling. At this moment there is only some information for biological materials. When these materials are not too much mixed up with non-biological or toxic materials, they can be returned to the biological cycle (e.g. composting), to restore partly the quality of the soil to grow biomass with the help of the sun’s energy. Thus, every biological material can be a producer of energy and serve as nutrient for new plants, after use (waste=food). In the case of processes for biological materials, a net energy production can result, for instance by making ethanol or methane gas. If we ensure that waste products from this fuel production process, and eventually the fuel itself can also be absorbed by plants and trees, then the soil, water and sun can take care of the upcycling.

Besides this biological material cycle, Braungart and McDonough distinguish a technological cycle. In this cycle we normally don't have the possibility to generate energy from the downcycling process and the upcycling of materials in a technological cycle requires energy. For instance a lot of energy is required to extract aluminium from used metal and to melt it for the production of new aluminium products. Upcycling of concrete and bricks is even more difficult. Use of stony construction waste as bulk material for applications like highway foundations is not a high-quality re-use (downcycling), and therefore cannot be considered as upcycling. The concrete granulate can also be used as a replacement for gravel in new concrete, which may be a higher quality use. But new cement mortar is still necessary to produce new concrete (i.e. the cycle is not fully closed). Closing the cycle by additionally extracting cement from used concrete is extremely costly and requires temperatures of 1400 degrees (a lot of exergy).

Building construction practice demonstrates that up till now there are few opportunities to use material flows in such a way that upcycling is possible. On the one hand, the arsenal of building products, materials and methods using renewable materials is limited, and on the other hand there is little expertise and knowledge of separation of construction waste that allows high-quality re-use. Besides creativity in the design of products and methods for upcycling of construction waste, up-cycling will almost certainly require a lot of energy.

At this moment we are not able to quantify the energy-use of all materials, but we can imagine that when we take the energy-use of materials into account, according to the cradle-to-cradle principle of upcycling, the energy needed to produce energy saving or energy producing techniques can outweigh the effect of the technique, thereby making it ineffective. To make better decisions for an energy efficient design, we should do more research on energy-use for upcycling materials. For now we know that upcycling can cost large amounts of energy and that we have to take this aspect also into account to determine the effect of a measure to reduce the primary energy demand. Thus we can prevent that the energy demand for energy saving or sustainable energy production will not cost more energy then there is saved respectively, produced.

3. Models for upcycling and downcycling

As mentioned before, upcycling, the conversion of a waste product into a high-quality material resource that fits into a cycle, is usually difficult, or impossible to achieve with current technologies and may also incur high energy costs. If upcycling is impossible, the result is a material of lower quality (downcycling) that may be used for another product. From an exergetic point of view the material is not lost, but it loses quality. In thermodynamics, this loss of quality, or the mixing up of materials, is called an increase in entropy or a decrease of exergy [2].

The two means of material (re)use have previously also been called cascading (downcycling), and re-cycling [3]. The terms downcycling, and upcycling coined by Braungart en McDonough, may well be better, and are at least better-known. What is less well-known is that, as far as we can make out, up- and downcycling are the only ways to make more efficient and effective use of material and energy flows. In practice we often come across combinations of down- and upcycling. Also it is not well-known how up- and downcycling are essentially different from each other.

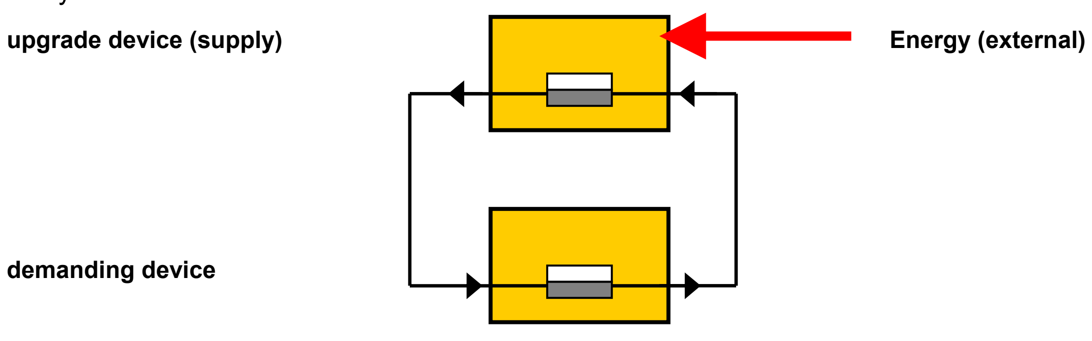

Figure 2: Recycling-circuit: upcycling (Leo Gommans -TUDelft).

The upcycling of materials costs energy which must be added to the circuit from the outside (fig. 2). For instance used steel from a machine must be separated, transported to a melt-oven, and then be given another life as “new” machinery or another purpose. Energy is added to the product in significant amounts to allow the product to function with a certain quality. Downcycling on the other hand, is characterised by low energy costs. When the product quality has deteriorated to the extent that its functioning becomes unsatisfactory, it may be used (in adapted form) for another purpose with a lower quality demand. Hence a cascade of functions arises from the flow of the original materials. Along the cascade the entropy increases and the exergy decreases (fig. 3). Examples of material flows in cascades are water that loses purity or electrical energy with initially a high exergy that decreases in the cascade and eventually gives low-temperature heat energy, useful for space heating in residences. In a sustainable future, materials must be upcycled and now we must start to do so, to give future generations the same possibilities as we have at this moment. This again, requires possibly significant amounts of (sustainable) energy.

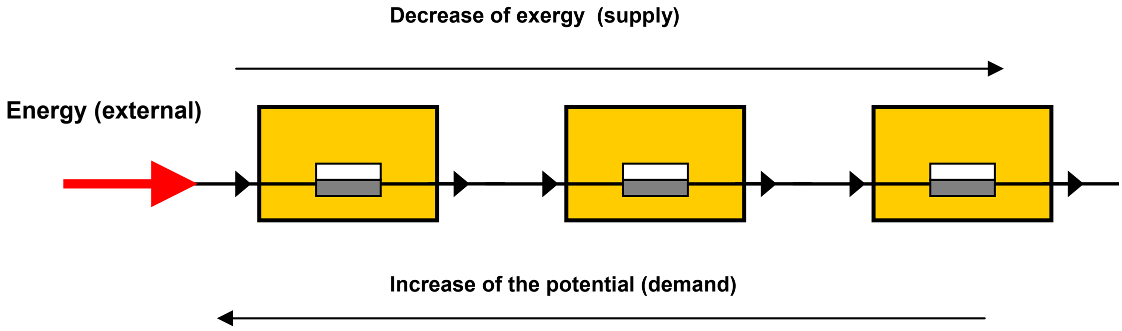

Figure 3: Cascading circuit: downcyclen . (Leo Gommans -TUDelft).

Downcycling is not always a sustainable option because it often results in waste materials that cannot be upcycled with current technologies, or only at prohibitively high costs. If a material cannot be upcycled, downcycling can still be an attractive option. The material is re-used with some energydemand and less new high-quality resources are required. This is more or less the way society currently deals with material resources. Eventually we end up with material that is stored in refuse-tips or burned. The chances that this waste material will ever be used for a high-quality purpose in the future are slim, and depend on new technologies which make it feasible to extract useful material components from the refuse. This has already led to new commercially viable activity in which old refuse tips are being processed to extract materials.

Braungart en McDonough advocate upcycling of waste products. From their point of view, downcycling leads to composites that never can be upgraded [1]. According to the authors, products should be made from renewable resources. In our opinion, products should be designed with complete re-use of materials in mind, as well, but this may also be possible with downcycling. In some cases we think that downcycling may be preferable because it costs less energy or material to make a product. These considerations should be kept in mind when designing a product such as a building, in addition to the ease of separation of components, allowing high-quality re-use of the materials at minimal energy costs.

4. The availability of energy and space

An interesting aspect of the cradle-to-cradle approach is that material use can be expressed in energy use for upcycling the materials. This energy use depends on the (efficiency of the) technology available for upcycling. The energy use therefore, is not fixed and will improve as technologies improve. Energy is an important factor in upcycling a material so that this material can be used and re-used endlessly. If material flow cycles can be closed so that upcycling is possible, depletion of material resources is no longer an issue. Upcycling will only require energy, lots of energy perhaps!

Energy is a resource that is currently largely extracted from fossil fuels, which are being depleted at the current increasing rate of exploitation and which are causing global warming. As a result we are switching to sustainable energy, mostly directly or indirectly derived from the sun (just as fossil fuels for that matter). The irradiation of solar energy of high-exergy quality on the earth is very large and time-dependent (day/night and seasonal variations). Fig. 4 is a well-known representation of the annual solar radiation, the world energy demand and the fossil fuel reserves. It shows that the amount of solar radiation is enormous compared to the world energy demand, suggesting that there is a lot of potential for upcycling material flows. In practice this potential will be severely attenuated, especially if we want to produce high-exergy energy, such as electricity.

In The Netherlands about 10% of solar irradiation on a pv-cell can be converted to (high exergy) electricity. Thermal solar collectors can convert up to 50% of the irradiation to heat energy. The resulting hot water has a limited maximum temperature and the energy has less exergy than electrical energy. Plants convert less than a percent of solar irradiation to biomass, but nonetheless are an important store of high (chemical) exergy. Biomass also supplies food and fodder, construction material, maintains or possibly increases biodiversity, reduces the airtemperature by evaporating water and binds carbon dioxide. So growing biomass is a multi-effective way of collecting solar energy. For the production of technical appliances in particular, much material is required.

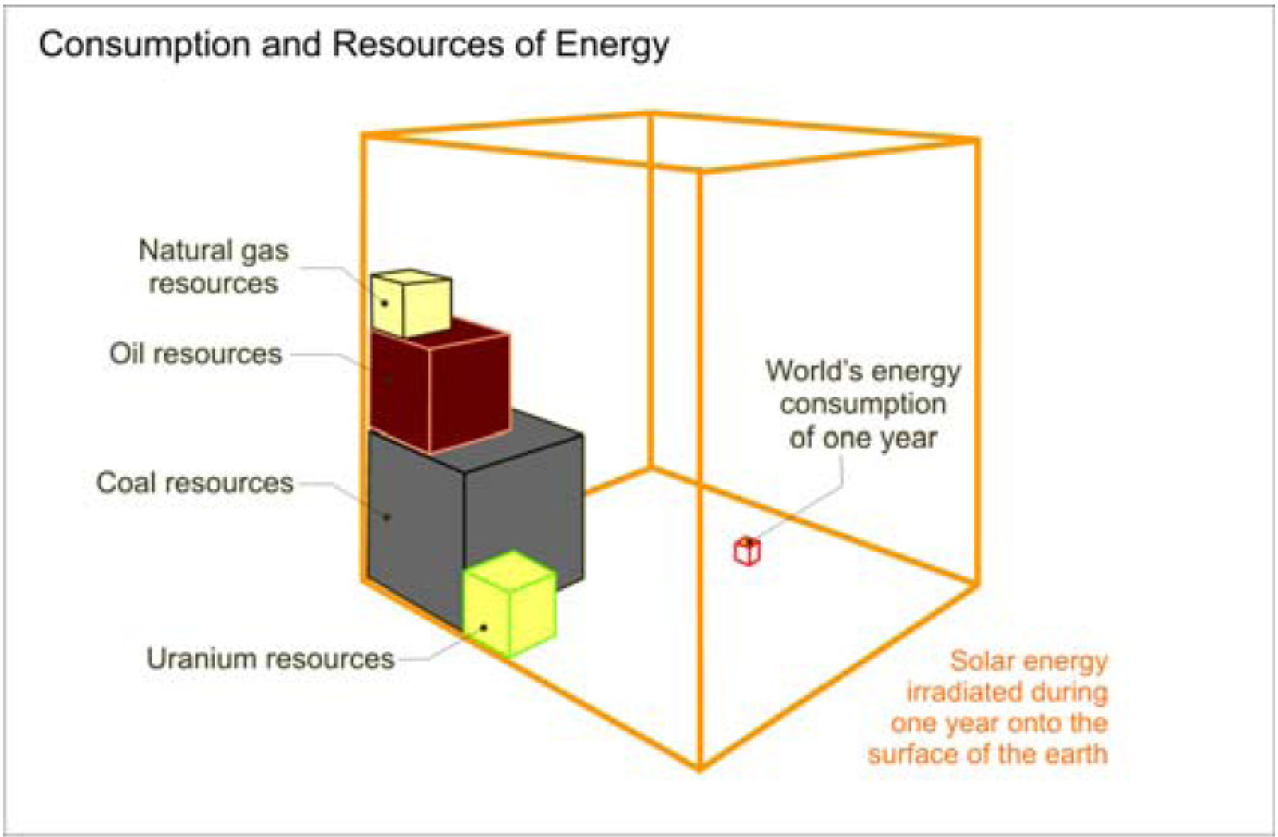

Figure 4: Yearly world's energy consumption in relation to all fossil fuels and the solar energy radiation on the surface of the earth (Krauter 2006, p2; adapted from Greenpeace) [4]

Material use requires energy use and the production of energy requires space. Thus saving energy and using energy effectively from renewable sources will be an important factor to take into account when making spatial planning decisions. Biological materials are one of the few materials that can currently be upcycled. The upcycling processes take time and cost energy and space, for plants to collect nutrients from the atmosphere and soil, so they can grow. The relation between material use and space requirements is more or less clear-cut for biological cycles. For technological cycles upcycling material flows can only be expressed in terms of energy and exergy which can in turn be associated with a certain area of the earth's surface and a certain solar radiation necessary to produce it. Sometimes more than one energy conversion technology can be used in the same place (e.g. wind turbines in a rape seed oil field, or in a field of PV-cells)

In any case, material and energy use, requires space. Often the space requirement also impinges negatively on the biodiversity. Biodiversity is the diversity of genes, species and ecosystems in a given region [5]. It is a measure of the quality of an area. In 1992, 186 countries signed a treaty in Rio de Janeiro, in which they committed themselves to identify, monitor and protect the biodiversity in their own countries. The treaty indirectly defines limits within which we can manage space, material flows and energy use. For sustainable building and development in general, we must call a halt to the detrimental effects on biodiversity, and better still try to increase it. It is clear however that space is increasingly becoming a scarce commodity. The growing world population and wealth puts pressure on the biodiversity, which can be relieved by a change in human behaviour and (bio)technological solutions.

Although figure 4 shows there is enough solar energy on our earth, this energy is not always there in the desired form and not always available at the right place and time [6]. Therefore we need to convert, transport, respectively store the energy, which will cost materials, space and energy for the chosen (bio)technological solutions. As far as we can express material use in energy use and as far as we relate the energy-use to a certain amount of earth surface, a sustainable environmental plan is as much a matter of effective use of (solar) energy, as it is a matter of effective use of space: On our earth surface, space is energy and energy is space.

5. Conclusions

The exploitation of the earth's surface for shelter, food, materials and energy, and the associated land use for the benefit of "civilised" man, has its limits if we want to achieve a sustainable environment. Effectively dealing with this environment by limiting the use of scarce resources and the optimal use of these resources by down and upcycling and improving biodiversity, are conditions for sustainable development.

The fact that material and energy use is related to space and the quality of this space (biodiversity), makes it easier to make sustainability of plans measurable, although a sustainable environment is not easy to achieve. The effective use of available space, materials and energy without damaging biodiversity, is a challenge for the designer, builder and user. The Cradle to Cradle approach has only recently become wide-spread and there is still a long way to go. From this early stage we all should develop this approach to achieve a sustainable society.

The improved understanding of the relationship between materials, energy and space, from an exergetic point of view, gives us the conditions for the development of principles that help to make decisions for an effective spatial design regarding the use of fossil fuel energy. It is possible that the use of material for energy saving techniques costs more energy in the future (to upcycle), than the energy that is saved today. It is also possible that a certain technique uses a lot of space or reduces biodiversity more than another technique does. The total chain of the techniques for the spatial alternatives have to be taken into account; conversion, transport and storage of energy. The principles of upcycling and downcycling can be applied in the spatial plans in several ways with several techniques

For the design of today’s regional environments, with a strong competition for space material and energy for the needs of mankind and the subsistence of life on this earth, it is necessary to have the information on principles and considerations, for planning the right alternatives on the right place, in order to find effective spatial solutions that help us to achieve a more regional sustainable future!

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