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Review

Energy costs of energy savings in buildings: A Review

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Abstract: It is often claimed that the cheapest energy is the one you do not need to produce. Nevertheless, this claim is somewhat unsubstantiated. In this article, we try to shed some light on this issue by using the energy return on investment (EROI) as a yardstick. This choice brings semantic issues because the EROI is used in a different context than that of energy production. Indeed, while watt and negawatt share the same physical unit, they are not the same object, which brings some ambiguities in the interpretation of EROI. These are cleared by a refined definition of EROI and an adapted nomenclature. This review studied the research in the energy efficiency of building operation, which is one of the most investigated topics in energy efficiency. Impact of insulation, high efficiency windows, and other energy efficiency measures were considered. These results were normalized for climate, life time of the building, and construction material. In many cases, energy efficiency measures imply a very high EROI. Nevertheless, in some circumstances, this is not the case and it might be more profitable to produce the required energy than trying to save it.

Keywords: Biophysical economy; life cycle assessment; EROI; passivhaus; insulation.

1. Introduction

Energy efficiency is a key tool to tackle two of the biggest challenge facing humanity: climate change and energy scarcity. Indeed, to avoid catastrophic climate changes, it is generally acknowledged that the world needs to reduce the CO_2 emission by 50% from the current level by 2050 [1]. For developed countries, this translates into a reduction of 80%, a factor five with respect to 1990 emissions. While, increases in renewable energy production can help to reach this goal, some authors have proposed instead to drastically reduce the energy consumption.

For instance, Kesselring and Winter [2] proposed the concept of a 2,000 W society which aims at consuming no more than what corresponds to an average continuous power of 2,000 W per capita; the value being considered as a fair share of the world energy consumption maintained at a sustainable level. This concept was later further developed and expanded [3,4]. Since actual rates of energy consumption is about 6,000 W in Europe and even 10,000 W in North America, this would certainly imply dramatic changes in day to day life for most of OECD countries.

Transportation is often singled out as the main target for energy efficiency. However, building industry has an even larger energy and environmental footprint as it is one of the human activities with the largest environmental impact. As noted by Dixit et al. [5], the construction industry depleted two-fifths of global raw stone, gravel, and sand; one-fourth of virgin wood; and it consumes 40 percent of total energy and 16 percent of fresh water annually [6-12]. These figures are more or less similar in any developed country. Indeed, for OECD countries, energy consumption by buildings varies between 25%–50% of total energy consumption [13], whereas it is closer to 50% in the European Union [14].

In these conditions, building industry is an obvious target for energy efficiency. This is the rationale behind the European Union Directive on Energy Performance of Buildings [15] that requires member states to implement energy efficiency legislations for buildings, including existing ones with floor areas over 1,000 m^2 that undergo significant renovations. The French legislation [16] specifies that by January 2013, any new building will have to consume less than 50kWh/m^2/yr. By 2020, all new buildings will have to be at least net zero – that is involving a consumption of 0 kWh/m^2/yr – or better, that is globally producing energy [16]. In a similar way, the Swedish government promulgated a Bill on Energy Efficiency and Smart Construction, to reduce total energy use per heated building area by 20% by 2020 and 50% by 2050, using year 1995 as the reference [17]. In addition, these energy efficiency measures offer a significant opportunity to reduce CO_2 emissions [1, 18].

Such ambitious goals in energy efficiency improvements raise the key issue of the efficient allocation of resources. Actions that need a large upfront investment for a minimal reduction of the energy consumption are undesirable. In some cases, the return might be so small that one might wonder if it would be better to produce the energy than trying to save it. This is true both for economic efficiency and ecological efficiency. This paper addresses this key issue.

2. Results and Discussion

One potentially useful alternative to conventional economical analysis when it comes to evaluate the sustainability of a particular solution aimed at saving energy (and consequently greenhouse gas emissions) is the net energy, E_{net}, analysis. The concept relies on the estimation of two parameters depending whether energy production or energy savings is considered. In the first case, all energy required to implement a particular equipment or process (from cradle to grave) is accounted for: it is celled energy invested, E_{invested} . Then, all energy that this device or process will generate or produce, E_{produced}, during its lifetime is evaluated. Then the net energy is simply:

$$E_{\text{net}} = E_{\text{produced}} - E_{\text{invested}} \tag{1}$$

In the second case, energy savings are considered. For this case, E_{produced} is replaced by E_{saved}. The savings , E_{saved}, are estimated for the difference between the amount of energy that the device, building or process should have require provided nothing is done and the amount of energy it should consume with the implementation of the proposed device, building or process. On the other hand, E_{invested} does not account for the energy used by the device after the measures of economy are implemented. In this case, E_{invested} only accounts for the energy required to implement the solution or install the equipment (from resources extraction to commissioning not from cradle to grave). The energy used by the solution is already accounted for in the definition of E_{saved}.

$$E_{\text{net}} = E_{\text{saved}} - E_{\text{invested}} \quad (2)$$

This analysis deals with the calculation of the ratio of the energy savings by a particular solution (over a given period of time) or the energy produced by some equipment or process to the energy required to implement the solution or install the equipment (from resources extraction to commissioning). This net energy analysis is sometimes called the assessment of energy surplus, the energy balance method, or the energy return on investment (EROI) [19-23]. In the case of energy production, the EROI is calculated from equation (3):

$$EROI = \frac{Energy_{produced}}{Energy_{invested}} \quad (3)$$

The key challenge to obtain a meaningful value for this ratio is to correctly define the boundaries of the problem which is investigated and to include all the inputs and outputs in the process [22,23]. For instance, the production of gasoline should account for all the steps required to produce it and deliver it to the stations as in a life cycle analysis (LCA). Of course, the higher this ratio, the lower the environmental impact per unit of energy is expected since less input is used for the same output and consequently less impact is felt by the environment [24]. It is likely to be linked with a better economic investment since the energy content is closely – but not necessarily linearly – related to the price of a product, a process or a service. As a result, energy sources involving a better EROI should be selected in preference to others [25,26]. This is especially true for renewable energy sources for which the environmental burden comes mostly from the extraction of the resources and fabrication of the energy systems prior to their use.

Calculating the average *EROI* for an energy basket is complex. Nevertheless, they are some indications that the average *EROI* of the US energy basket is close to 10 and that a lower *EROI* should induce negative economic impacts [27]. Hence, for purpose of this discussion acceptable energy solutions should respect *EROI* > 10. Hence, energy solutions with a lower *EROI* should be discounted.

A practical problem arises when using the EROI metric in a building application. There is a key difference between EROI calculated for energy sources and EROI calculated from energy saved. Hence, negajoules ($\not{J}$) and negawatt ($\not{W}$)[1] are compared to joules (J) and watt (W).

$$EROI = \frac{Energy_{saved}}{Energy_{invested}} = \frac{\not{W}}{W} = \frac{\not{J}}{J} \quad (4)$$

While at first glance this change of definition might look only semantic, it involves much deeper consequences. *EROI* was originally solely conceived for energy production or energy production

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[1] To our knowledge no symbols exist for negawatt and negajoules. Hence, we propose to use these one.

technologies and equipment. Hence, in this scenario energy produced and energy invested are both expected to be positive. In consequence, EROI will be always positive. Even when, the net energy production is negative, the EROI is still positive but smaller than 1.

For energy efficiency this is not necessarily the case. In rare circumstances, a poorly designed intervention might increase the lifetime energy consumption, which corresponds to a negative EROI since energy saved in negative. This situation might also be caused by a strong rebound effect, the Jevons paradox [28], where the users adapt their energy consumption behavior in a way that increases the consumption of a good or a service made more affordable due to the improved efficiency to a point that the new energy consumption exceed the original one.

Also, energy efficiency measures may cost nothing or even have a negative cost. Energy efficiency actions like changing thermostat settings or cooling by natural convection have zero or near zero costs which means that EROI→∞.

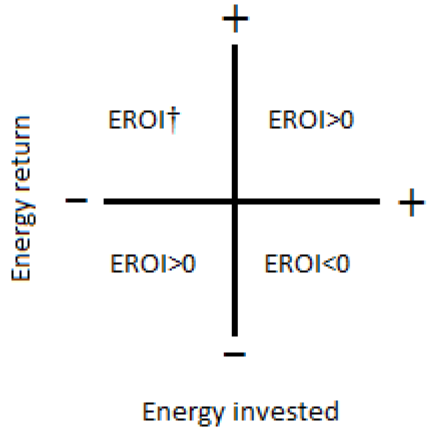
But, there is an even more favorable situation where an improvement of one aspect of a building has for consequence the optimization of the performance of others systems leading to an overall negative cost. For example, the improvements of the insulation of the building envelop produce given EROI for the insulation addition alone, but it may also allow for the reduction of the size of the heating system and hence produce saving on its embodied energy. This would lead to an overall lower total energy cost for the whole building, compare with the version with less insulation.

From the strict mathematical point of view this would produce a negative EROI (positive energy saved over a total negative energy cost). Hence, there is two types of negative EROI, one which is negative in term of energy savings and undesirable, and one which is positive in term of energy saved and highly desirable. Actually, this situation is better than EROI=∞ since the embodied energy is lower than the original situation! To distinguish these two cases, the symbol † is to be used instead of – for the case where the embodied energy is lower. To complete the picture, it should be noted that there are also the situations where the investment cost is negative and where the energy return is also negative. This situation is symmetric with the classical EROI and is treated the same way. These situations are described in the following diagram (figure 1).

There is another key difference between calculating EROI for energy efficiency application. The energy produced or saved it always calculated to a reference condition. For the energy production this reference is always equal to zero, while it is never the case for energy efficiency. Hence, adding insulation to a wall already well insulated have a much lower EROI than adding it to a poorly insulated wall. It is also important the energy payback time can be very long in building applications. In consequence, EROI may stay negative for a very long time and nevertheless reaches values above 10 since lifetime of building is very long (> 50 yr). Therefore, when analyzing the energy efficiency, the context is important and one must be careful when interpreting an EROI value.

In practice, few studies have been done on an energy basis most of them be carried on monetary return. Since, monetary value of energy unit is sensible to the nature of the energy input, EROI calculation based on monetary input shall be used with care. In average the energy content of a dollar of product and services is higher than its equivalent in energy, the EROI calculated in dollar without correcting for this factor is always smaller than the EROI calculated from energy unit (typically from a factor 6-10).

Figure 1. EROI class



Since, almost all studies where not designed to calculate EROI, all needed information is not directly available. While energy consumption is given in physical unit almost all the time, energy invested is not. However, it is possible to gather the information on the embodied energy content of the insulation material from alternate sources [29]. Nevertheless, this database is oriented to analysis done in the UK context, which may create severe distortions for other countries. In few cases, numerical values of the initial investment were not explicitly given in the text and we had to rely on measurement made on published graphs to get the appropriate information.

In other articles, the energy payback time (EPT) is given. The energy payback time is ta take needed to recover the energy invested trough energy saving or energy produced. By definition, it is the time after which the EROI reaches a value of one and the net energy is equal to zero. Hence, EROI over the life time is:

$$EROI = \frac{Lifetime}{EPT} \quad (5)$$

This brings the issue of lifetime of components [30-32] and the building itself, which are in general poorly defined. To handle this problem, it is often recommended to refer to the norm ISO 15686 *Buildings and constructed assets service-life planning* [33] or using a 50 years timeframe as a reference for major renovations, since it is acknowledged and used in many studies [34]. In our analysis, we use 50 years for the building life time and 35 years for the components lifetime.

There is other issue peculiar to building application. One of the key problems in building life cycle analysis arises from the long life of the buildings (30–100 yr). Over such a long period of time, the energy basket and even the climate are expected to change. This raises some concerns about the applicability of the standard life cycle analysis method for buildings [35-39].

Another peculiar aspect of the life cycle analysis of building is possible to exhaust resources locally even if the global resource based is immense. This problem exists for building material since they are bulky and therefore often expensive to transport of long distances. Hence, while the depletion of bulk resources is negligible at global level [40-41] and hard to put in evidence at the scale of a country like France, depletion becomes clear in a relatively small region like Île de France, where depletion time scale is the same order of magnitude than quarries or buildings lifetimes [42-43].

2.1 Insulation

Since a large fraction of the energy consumption in building is used for space heating or cooling optimization of the insulation is a critical issue. This is why optimization of insulation has been largely covered in the scientific literature. The oldest paper known to us is the work of Muncey in 1955 [44], who worked on the optimization of insulation for Australian houses. This study has been followed by many others [45-49]. For all of them, the optimization was based on economic consideration. The first and only article performing optimization in term of energy we have uncovered has been written by Anani and Jibril in 1988 [50].

Insulation a classic case of diminishing return, since the impact of each new layer is inversely proportional to the insulation already provided by the existing layers. In consequence, it makes no sense to optimize the EROI, since the very first layer of insulation as an infinite EROI. This is why to objective is to minimize the total lifetime energy consumption and then calculate the EROI for this configuration.

For a simplest case, energy consumption for thermal control over the building lifetime takes the form [51,52]:

$$E = \frac{86400\, U \cdot DD \cdot A}{\eta}\, N \tag{6}$$

where U is the thermal conductance of the wall, DD is the number of degree-day, A is the wall area, η is the efficiency of the heating or cooling system, and N the lifetime of the building. The equation is valid both for heating and cooling, but these contributions must be calculated separately.

The thermal conductance takes the form:

$$U = (R_w + R_i)^{-1} \tag{7}$$

where R_w stand for the thermal resistance of the original wall and R_i is the thermal resistance of the added insulation. Since thermal resistance increase linearly with the thickness of the insulation (t), the previous equation can be rewritten as:

$$U = \left(R_w + \frac{t}{k}\right)^{-1} \tag{8}$$

where k is the thermal conductivity of the insulation material. Energy consumption for temperature control is then equal to:

$$E = \frac{86400 DD\ \cdot A}{\eta\left(R_w + \frac{t}{k}\right)} N \tag{9}$$

The energy cost of insulation is defined simply as:

$$E_i = \varepsilon t A \tag{10}$$

where ε is the energetic cost per unit of volume of the insulation. The total energy consumed by the building over its lifetime is then equal to:

$$E_t = E_{h,c} + E_i = \frac{86400DD \cdot A}{\eta\left(R_w + \frac{t}{k}\right)} N + \varepsilon t A \quad (11)$$

To minimize the total energetic cost, derivation of E_t in respect to t is set to be equal to zero. The optimal insulation thickness is then equal to:

$$t_{opt} = 293.94\left(\frac{DDkN}{\varepsilon\eta}\right)^{\frac{1}{2}} - kR_w \quad (12)$$

From this value, we can now calculate the energy saved for heating and cooling

$$E_{saved} = \frac{86400DD \cdot A \cdot N}{\eta}\left(\frac{1}{R_w} - \frac{1}{R_w + t_{opt}/k}\right) \quad (13)$$

By substituting t_{opt}, we get

$$E_{saved} = \frac{86400DD \cdot A \cdot N}{\eta}\left(\frac{1}{R_w} - \frac{1}{293.94}\sqrt{\frac{\varepsilon\eta k}{DD\ N}}\right) \quad (14)$$

The invested energy being equal to:

$$E_{invested} = \varepsilon t_{opt} A \quad (15)$$

By combining these two elements, EROI is then equal to:

$$EROI = \frac{Energy_{saved}}{Energy_{invested}} = \frac{1}{R_w}\sqrt{\frac{DD\ N}{\eta}}\frac{1}{\sqrt{k\varepsilon}} \quad (16)$$

In the previous equation, only insulation properties can be controlled by design. Hence, we define the insulation quality factor:

$$Q_i = \frac{1}{\sqrt{k\varepsilon}} \quad (17)$$

From this simple first order analysis, we can see that EROI is inversely proportional to the wall existing insulation, to the square root of the lifetime cumulative degree-day scaled by the efficiency and inversely proportional to the square root of the product of the thermal conductivity. This simple relationship will be used to normalize the various reported return on investment analysis to a common DD, N, R_w and η. In addition, one shall note that the square root relationship between DD, EROI and optimum insulation thickness imply a smaller thickness and a larger energy consumption that obtained by a simple linear relationship.

To our knowledge, this behavior was not considered when translating the *passivhaus* standard [53] to other climate zones. Indeed, the standard in of kWh/m^2 is kept constant, while this standard should be relaxed if the minimum lifetime energy consumption is the goal, as in the original *passihaus* philosophy. This approach has the unfortunate consequence of increasing the overall energy consumption over the life time of the building compared to the optimal configuration by overinsulating it in the northern countries.

In recent times, optimization studies on insulation are mostly done in countries in economic transition. Especially, they are numerous studies done in Turkey [54-57]. This is fortunate since this dataset is essentially internally consistent, which help to point the underlying factor affecting the EROI.

The data from these studies have been normalized to a 50 years lifetime (figure 2). In addition, to reduce dispersion of the data point we have limited our analysis to the cases were polystyrene was used as an insulator. The residual dispersion comes from the economic assumption at the basis of the optimization and the original uninsulated wall thermal resistance. The square root relation between heating degree-days and the EROI can easily be observed.

We have also calculated what would have been the optimum EROI based on the physical data given (figure 3). Since economic assumptions are now absent, the dispersion is much lower. It is dominated by the variation of the wall thermal conductivity in the absence of insulation. Overall, the optimum EROI tend to be lower the published value from the literature since the economics optimization is done a shorter lifetime (10 years).

It should be pointed out that air in a cavity is itself is a good insulator [57-60]. Taken at face figure its $Q_i=\infty$ since it cost nothing. However, in practice the situation is more complex. For example, in the previous papers, an air cavity is placed within a wall. In these cases there is no additional cost associated to the air confinement. But, since the air cavity allows the utilization of a thinner insulation, its cost is negative, while improving the overall insulation and the net energy saved compared to a wall without the air gap. Hence, from the data of Mahlia and Iqbal [60], EROI of the air gap is between †0.7 and †8.7, since the air gap allows a reduction of the embodied energy in the insulation.

2.2 Windows

Windows are the most critical component of the building envelope for energy efficiency. They are literally holes in the walls allowing heat or cold to enter. In consequence, any improvement in their insulating properties has a very large impact on energy consumption. This is why the energy return on investment is usually very high. In addition, windows provide natural daylight that largely reduces the energy consumption for lighting. Nevertheless, optimizing the adequate of amount is a rather complicate tradeoff for the optimization of the overall building efficiency.

The oldest article, we have been able to find on the energy content of windows has been written by Saito & Shukuya in 1996 [61]. These authors studied three types of window: single and double glazed with aluminum frame and double glazed with a wood frame. Calculations were done for a glazing of 1.02 m^2. Mass of the aluminum frame was estimated to be 4.1 kg, while a single glazing panel 3 mm thick was estimated at 7.6 kg. Energy density of glass and aluminum was estimated to be 16.9 MJ/kg and 503 MJ/kg respectively. In absence of precise data, they assumed that the wood frame embodied energy was one tenth of the aluminum one. Hence, for the three windows type the embodied energy was 2190 MJ, 2319 MJ and 463 MJ. Then they calculated the heat transmission trough the frame and glazing to be equal to 8.0 W/K, 5.2 W/K, 3.7 W/K respectively. In consequence, the energy saving for the Tokyo climate (1800 HDD) using the single window pane with aluminum frame as a reference is 436 MJ/yr for the double glazing, with an aluminum frame and 669 MJ/yr for the wood frame with double glazing. This translates in an energy payback of 108 days and -2.6 yr respectively using the single glaze window with an aluminum frame as reference. Based on a 35 years lifetime, the respective EROI are 118 and †13.6 since the wood frame has a negative energetic cost compare to an aluminum one.

Figure 2: Calculated EROI from literature data normalized to a 50 years lifetime

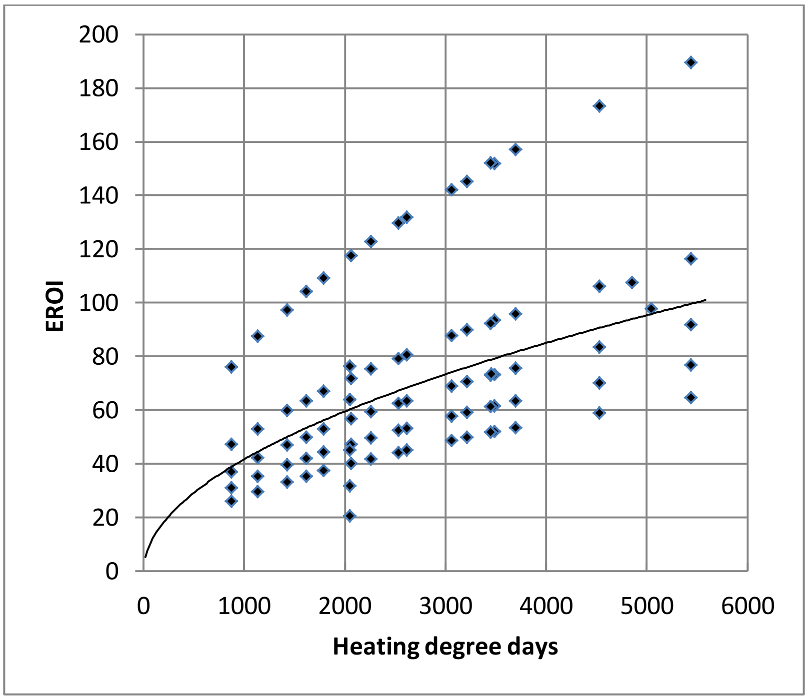
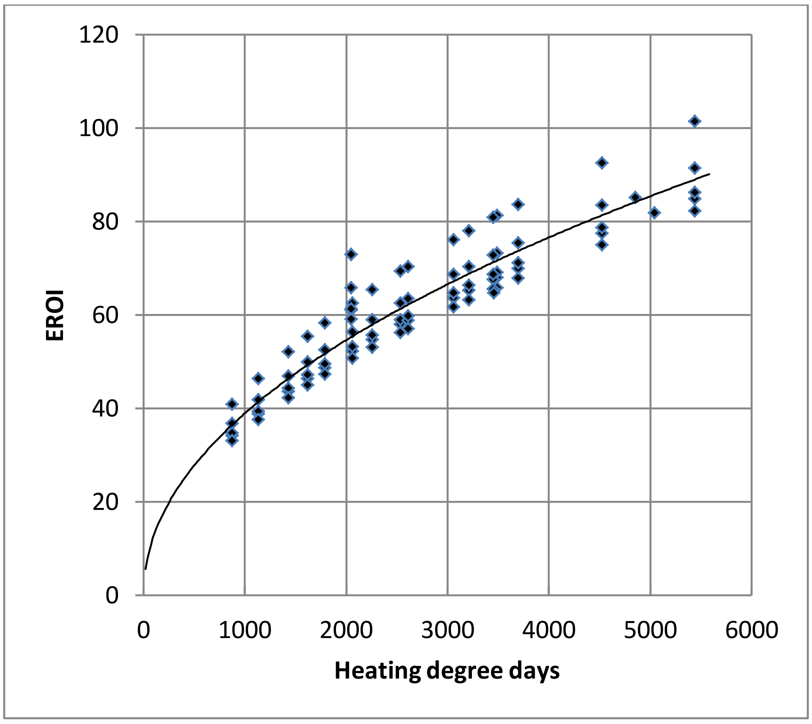


Figure 3: Optimized EROI for a 50 years lifetime



While not described by the authors, single glazed wood framed window would have an embodied energy of 335 MJ and a conductivity of 6 W/K. Energy saving compared to this reference are, for double glazed window with aluminum and wood frames, 124 MJ/yr and 358 MJ/yr. In consequence, respective EROI are 2.2 and 98. It is the aluminum frame that kills the performance, illustrating the importance of analyzing the window as a system and not only focusing on the glazing.

An extensive study of life cycle analyses of windows has been carried by Weir in 1998 [62] in the British context [62,63]. She studied many aspect of the windows design. Especially, she studied the utilization of noble gas to fill the window gap. For a 1.2 m ×1.2 m window, the additional energy cost of filling the gas with argon, krypton and xenon was estimated at 11.83 kJ, 502.2 MJ and 4.5 GJ. This calculation included the reduction of optimum thickness of the gap (16 mm, 12 mm, 8 mm from 20 mm with air) but not its effect on the embodied energy of the frame. The window being based on a timber core with an aluminum cladding, the embodied energy of the windows excluding the gas was estimated at 1030.5 MJ. Addition of argon reduced the U-factor of the window from 1.63 W/m^2 to 1.3 W/m^2. Assuming 2810 heating degree-day [UK average, 64], energy saving over 35 years for the argon would be 2.8 GJ, which provides an EROI of 237 000! This extreme value raises question about the estimated value of the embodied energy of argon. Values of the U-factors are not given for krypton and xenon windows. Nevertheless, from the figures given in the article we can estimate the energy saving to be respectively twice and triple of the argon saving. Accordingly, respective EROI are 11.2 and 1.9.

Later, the same authors produced a seminal study [65] on energy efficiency of windows. They examined the embodied energy and their impact on energy consumption of five configurations of windows to be used for the replacement of existing ones in four building sited south of Edinburg, UK. For this comparison, it is possible to calculate the impact of adding a layer of low e coating, a glazing or including a buffer gas (argon or krypton). Accordingly respective energy payback time and EROI over 35 years can be calculated:

- Addition of low e coating on a double glazed window: 17 days and 22 days, EROI=592-758
- Addition of argon to a low e coated and doubled glazed window: EROI=125,000-134,000 (Doubtful, will be discussed later)
- Addition of krypton to a low e coated and doubled glazed window: EPT=4.25-11 yr, EROI=3.2-8.2
- Addition of a third glazing and an additional low e coating to a low e coated and doubled glazed window with argon filling: EPT= 1.4-1.9 yr, EROI=18-25.
- Addition of a third glazing and an additional low e coating and krypton to a low e coated and doubled glazed window with argon filling: EPT= 9.6-12.8 yr, EROI=2.7-3.6

From these numbers, it is clear that it makes little sense to use krypton as an insulating gas, while argon and low e coating are very effective energy investment. Addition of a third glazing and additional low e coating is also a good solution. Indeed, the authors conclude that double and triple argon filled windows are the best options in their climate.

Nevertheless, these values are calculated as an additional feature to a new window. Replacement of an existing window by a new one is much more costly in energy. Hence, replacement of an existing double glazed air filled window with the same window with low e coating and argon insulation has a payback time between 4.2 and 4.9 years (EROI=7.2-8.3). It should be noted that the frame of these replacement windows was made of aluminum cladded timber, which is among the less energy intensive type [66]. Others types would have an even lower payback. Loss of embodied energy of the original windows and upfront cost of the new ones raises the question of the pertinence of replacing the whole window instead of simply restoring it [67]. Alternatively, replacement should be done when the old windows reaches its end of life to avoid wasting its embodied energy.

An interesting aspect of Menzies and Wherrett paper [65] is that costs are calculated both in energy units and in monetary unit. Calculated monetary payback times are much larger than energy payback time. For low e coating the ratio is about 90 and a staggering 30,000 for the addition of argon, while it is between 6 and 12 for the addition of an additional glass pane. These last ratios are expected since they are close to the average societal EROI [27]. However, large ratios for the argon and low e coating can be caused by an erroneous life cycle analysis or simply by the fact that the vendors make a very large profit margin on these features. While this is difficult to prove for the low e coating, it is much easier to test in case of argon. Based on the comparison of data from [65] to the present argon market price, added argon in windows was sold at roughly 200 times its today market price. Nevertheless, the same price converted in energy using the average energy intensity of the economy predicts an energy content of argon roughly hundred times larger than the one calculated in [65]. In consequence, true EROI is likely to be much lower than the previously calculated EROI (>100,000) and is likely to be in the range of a few hundred. This is still very high and similar to the addition of low e coating.

3. Conclusions

From this preliminary review of the scientific literature, we have compiled the EROI from two energy saving strategy: insulation material and advanced windows. Estimated EROI are high compared to most energy sources [24]. This illustrates the strongly positive impact on energy conservation on the environment. In consequence, to motto "*The cheapest energy is the energy not used*." is true in most case we have observed.

Nevertheless, the diminishing return of more insulation raises the possibility that passed some point one is better to produce the energy than trying to save it. This question is especially important in the light of policies that simply copy the *passivhaus* standard without further optimization to the local climate. The same situation arises when extreme energy consumption reduction is sought at the expense of the embodied energy.

Expanded version of this work will include more studies and provide a much wider survey of the energy saving technologies.

Conflict of Interest

"The authors declare no conflict of interest".

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