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Economic models to evaluate energy costs: Are externalities and energy accounting the answer?

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Aim: In the context of climate change this paper explores the value of models for evaluating energy costs by considering energy accounting and externalities instead of capitalistic economics.

Research methods: We test the hypothesis that the conventional economic model of the energy market can lead to inappropriate choices, and that those choices may be environmentally damaging. We examine energy accounting (energy return on energy investment), embodied energy and the incorporation of external costs as more valuable economic models.

Findings: This paper reviews existing economic tools and examines modifications, which, when applied to energy provision or efficiency and conservation of energy applications, may give more accurate information about investment, return and environmental damage. Energy accounting of schemes should be a preliminary requirement for all proposed energy schemes. Externalities are less readily applied, but as the costs associated with renewable energy are becoming competitive in conventional economic terms, they are less valuable than energy accounting.

Value of the paper: The paper concludes that a preliminary assessment of a proposed energy scheme should be undertaken using energy accounting and external costs to determine the true energy value. These models could be used to select the best environmental option. Indeed "energy uneconomic" schemes, which cost more energy than they deliver, should be abandoned in order to avoid unnecessary environmental damage. After this process, legislation and fiscal measures such as taxes and incentives could be applied to satisfy social and political imperatives. Examples of energy accounting in insulation and consideration of external costs in a proposed strategy to replace fossil-fuelled electrical generation in Indonesia are included in the paper.

Limitations: We have not considered the serious question of finite fossil fuel resources and feel that this would be a profitable line of research.

Keywords: Embodied energy, energy accounting, externalities, renewable energy
JEL: F64, H23, L71, L72, Q40.

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1. Introduction

The British prime minister, Boris Johnson, said that capitalism and greed had solved the UK COVID crisis (Guardian 2021), suggesting that it was the drive for profit that had led to the successful development of COVID vaccines. There has been much criticism of Johnson for this claim, which he immediately tried to retract, with many pointing out that altruism and concern for humanity had a much greater impact. Here, we consider the role of capitalism in the equally important issue of Sustainable Development.

Sustainable Development was defined by the Bruntland Commission (in 1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". It seems self-evident that simple capitalism will not, or can not, achieve this as there is no value placed on finite resources or environmental damage. To put this into perspective for energy consider the Reserves to Annual Production (R/AP) ratios reported by BP in their annual review (2021); of 48.8 years for natural gas, 58.5 years for oil and 139 years for coal. These fossil fuels (except for coal) can be expected to last for less than a single human life span and although new reserves may yet be discovered, they are likely to be in increasingly inaccessible locations. Not only will this make them more expensive, but in areas such as the Arctic, which, ironically, is becoming less inaccessible due to Global Warming induced melting of the ice cap, there are already rival claims and potential conflict over ownership. The second issue that arises from the exploitation of fossil fuels is the emission of carbon dioxide as a combustion product. Burning a tonne of fossil fuel yields around 3.5 tonnes of carbon dioxide. Thus, continuing to utilise fossil fuels will add to the 1.5 trillion tonnes of anthropogenic carbon dioxide already in the atmosphere and provoke further global warming. The price of fossil fuels is largely controlled by OPEC and does not reflect the limited reserves, and the cost of environmental damage caused by burning fossil fuels is not borne by the polluter but paid by everyone in terms of poor air quality (and therefore health) and in terms of the impact of climate change. Recent flooding events in Europe and heat waves in North America are attributed to climate change, indeed the most recent IPCC report indicates that the 1.5°C tipping point will be reached within two decades (IPCC 2021). Despite decades of evidence of the link between burning fossil fuels and climate change, little has been done to attenuate the use of fossil fuels. This inaction can be blamed on politicians, vested interests, and the demand for continuous financial growth. Fossil fuel rich countries generally want to exploit their assets for financial benefits.

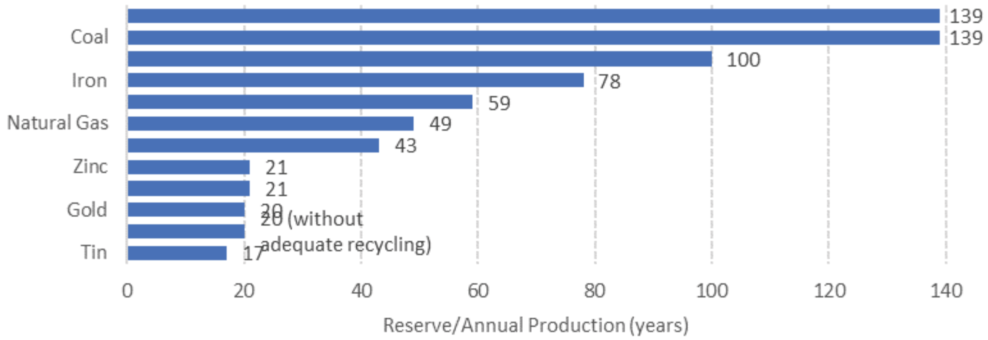
Mark Carney (2020), former governor of the Bank of England and now special envoy for climate action and finance at the UN, laid out the economic imperatives on Climate Change in his 2020 Reith Lectures. Among the many excellent points that he made are: how much we value Amazon the company compared to how little we value the Amazon rainforest, and how philosophers have, for centuries, questioned the low value placed on water, but in relation to the present discussion: the current global financial system, through investments in climate damaging technologies as a whole, is funding a temperature increase heading to over 3°C. Carney recommends a new financial requirement, which would help to bring the Earth on target to net carbon zero in order to meet a 1.5°C temperature rise limit as agreed at COP21 in Paris (2015). Carbon taxes, meant to encourage emitters to attenuate their carbon emissions are hardly effective at the generally levied \$3/tonne, whereas Carney says that there are estimates that \$75/tonne is needed by 2029. Existing technologies, when applied at scale, can economically reduce about 60% of emissions, keeping the Earth on track for net-zero, consistent with 1.5°C. However, we do not yet have commercially available technology to cut any more than 25% of anthropogenic greenhouse gas emissions. Thus, Carney argues for a new world finance reporting mechanisms to push investors into a virtuous circle of supporting net-zero projects.

The current provision of energy is heavily reliant on fossil fuels, but as these are resource limited and contribute to global warming, they do not assure a sustainable future. After briefly exploring the resource issue we go on to consider alternative ways of evaluating energy schemes for their environmental impact. We therefore examine energy resources such as fossil fuels and renewables as energy provision, but also consider measures for conserving energy such as thermal insulation of a building, and energy efficiency measures such as superior electric light bulbs. In all cases, consumers will tend to be drawn to the lowest capital cost. We argue that that cost does not necessarily reflect the true environmental cost. This may be because the market price only represents internal costs – and not the external impacts of resource depletion and pollution. It may be because the energy, or energy commodity is locally taxed or subsidised. However the cost is influenced, we argue that all aspects of energy should be subjected to a preliminary evaluation to assess their net energy contribution and environmental impact before a decision to proceed with them.

All of our mineral resources are finite, but some are particularly limited, see

Figure *1* for a partial list, and have extremely low reserve/annual production (R/AP) lifetimes. This requires urgent attention since much of humanity depends on manufactured equipment for its very survival and without these resources, we could not manufacture electrical goods, but much more importantly we could not generate or transmit electricity, rendering heating/cooling of buildings impossible and storage of food a challenge. In fact, all aspects of modern life would be a serious challenge. The R/AP values are low against a human life span, let alone against the span of human history or geological timescales. The move to electric vehicles is heralded as a positive move in the strategy to avoid greenhouse gas emissions, but the projections by Greim et al. (2020) are that we will exhaust the world Lithium resource in just 20 years. That is unless the recycling rate reaches over 95%, in which case Lithium reserves might last 100 years. Stretching the R/AP value by a factor of five is a help, but ultimately not a long lasting or sustainable solution. We already see countries chasing these rare resources, for example China has significant and growing influence in Africa, and Greenland – see Marshall (2015) and Dams et al. (2020). Current economic models are incapable of placing a value on such resources: if we exhaust a resource, we clearly do not leave it for future generations. Schumacher (1973) addressed these issues in his book "Small is beautiful", in which he demonstrated how quickly growth could deplete finite resources. In the intervening years, very little has been done to limit growth: in fact, capitalist societies depend on continuous growth. Keynesianism works by stimulating consumer demand to promote economic growth, and as Monbiot (2016) concludes, consumer demand and economic growth are the motors of environmental destruction. Clearly with such small quantities of resources remaining, continuing to extract them is unsustainable. New concepts of thinking of time in geological terms are being explored by a Finish company looking for mechanisms to store nuclear waste for the order of 1 million years (Crease 2021). They have found that our thinking is extremely limited: at least in terms of time. We find it difficult to imagine what problems society might face in thousands of years, and indeed what long-term solutions are needed. This is beyond any previous human construction.

Figure 1. R/AP values for selected materials



Approximate values from various sources, see Jowitt et al. (2020) and BP (2021) for crude oil, coal and natural gas.

2. Climate change

In this paper, we address the equally urgent and vital issue of energy in relation to climate change. The causes and effects of climate change are well reported (see IPCC 2021). The need to convince Climate Deniers may have delayed the execution of serious strategies to minimise carbon dioxide emissions. The Precautionary principle (to take an action to meet a challenge even if that challenge has not been proven to exist) should have been applied as soon as the enhanced greenhouse effect was evident, just as in the 17th century, Blaise Pascal (C17) so wisely offered a pragmatic reason for believing in God: even under the assumption that God's existence is unlikely, the potential benefits of believing are so vast as to make betting on theism rational. So, we should have immediately restricted the burning of fossil fuels and should have done this by any means possible. Of course, countries and companies selling/exporting fossil fuels would object to any reduction in their income: users of fossil fuels would claim that it is uneconomic to use alternatives such as wind or solar power, and nations would argue that executing a unilateral action would put them at a disadvantage, whereas unanimous agreement between interested stakeholders to act cooperatively and for the common good was highly unlikely.

On a technical note, greenhouse gasses (GHG) such as carbon dioxide, methane, CFCs, etc. take years or decades to rise in the atmosphere and become effective, and when they do, they reside in the upper atmosphere for years, hundreds of years or even thousands of years (see EPA 2021). This means that we have yet to see the full impact of greenhouse gas emissions from the past decades: there is nothing that we can do about GHGs already released, other than to wait for them to act to enhance the greenhouse effect. Thus, the need to take urgent action to reduce emissions. Stern (2006) in his report commissioned by the UK Government, advocated spending money as soon as possible to ameliorate climate change rather than wait to make sure that Climate Change is a reality: such a delay would invoke a much greater economic cost. In his book, *Why are we waiting?* (Stern 2015) he returns to this question.

3. Energy returned on energy invested

The main source of energy for economic growth to date has been our reliance on finite fossil fuel reserves. Indeed, times of recession have usually been preceded by constricted economic access to these reserves. Economists have traditionally deployed net energy analysis tools to identify long-term trends between energy and economic growth. A key analysis tool that is greatly favoured is energy return on energy invested, commonly shortened to energy return on investment (EROI). It offers a means of measuring the energy surplus of various fuels by calculating the difference between the energy delivered to society and the energy invested in the capture and delivery of that energy. In simple terms, the units of energy delivered, divided by the units of energy required to deliver that energy.

The term was first coined by Hall et al. (1979) in their analysis of fossil fuel production in the US, where it emerged as a method of identifying how easily fossil fuels could be extracted, whether for a single well, an oil field, nationally or regionally. During the start of the oil rush, in the early 1900s, extraction sites were particularly easy to exploit, with EROIs of ~1,000:1, i.e., it required the energetic equivalent of just one barrel of oil to produce 1,000 barrels of oil. Today, applying a similar EROI methodology to oil yields leads to values of around 30:1 – depending upon the method of extraction (Brockway et al. 2019).

Different boundaries can be used to define the EROI for a particular energy source, resulting in decreasing EROI values as the definition is broadened to become more inclusive of an energy sources' societal and environmental impact. Murphy et al. (2011) provides methodological approaches for calculating various EROI definitions and these are summarised, here:

Standard Energy Return on Investment ($EROI_{ST}$) is applied at the point of extraction and is the energy used during extraction (termed 'direct energy') plus the energy used offsite to produce the equipment used on-site (termed 'indirect energy'). In efforts to make this metric more applicable to non-fossil fuel sources, it is sometimes now referred to as EROI at the primary stage ($EROI_{PRIM}$).

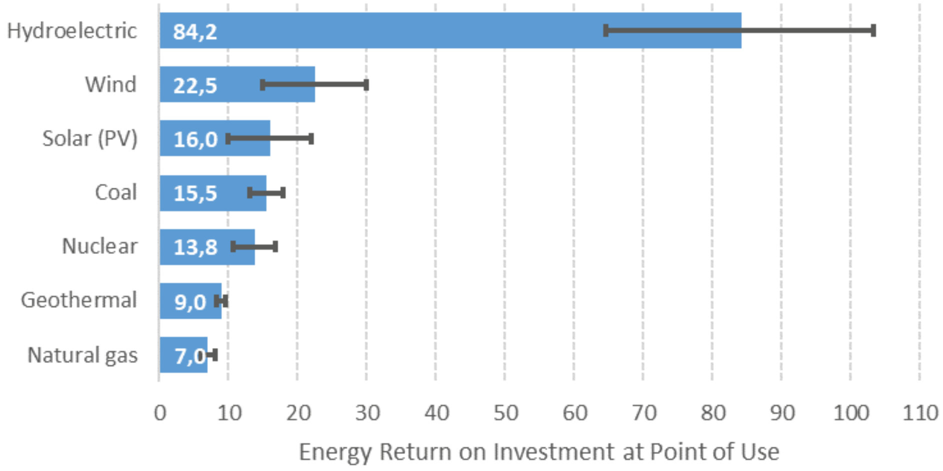
Point of Use Energy Return on Investment ($EROI_{POU}$) is more comprehensive and includes energy used for refining and transportation. In other words, the energy consumed in producing the 'useful' form of the energy source (i.e., the fuel) and moving it to its final point-of-use. This is sometimes now referred to as EROI at the final stage ($EROI_{FIN}$).

Extended Energy Return on Investment ($EROI_{EXT}$) provides a more comprehensive definition and considers not only the energy used in moving the energy source to its final point-of-use, but also the energy consumed in producing the infrastructure throughout the supply chain.

As boundary extents are expanded in attempts to capture wider societal and environmental impacts, definitions become blurred and comparisons between fossil fuel sources and renewable energy technologies more contentious. See, for example, Ferroni et al. (2016), who calculated an EROI for solar PV (roof-mounted and free-field placement) in Switzerland of 0.82 ±15%, essentially demoting solar PV at higher latitudes to the status ‘energy sink’. In a rebuttal of this work, Raugai et al. (2017) calculate values of 9-10. Further rebuttals ensued, which mainly highlight the problems of fair boundary placement when using $EROI_{EXT}$.

When comparing renewables and fossil fuels, a whole host of issues can lead to skewed assessments, like those around high up-front costs for renewable projects, and balancing costs for intermittent renewables. Whilst fossil fuels often have higher EROI values at extraction ($EROI_{ST}$), this does not allow fair comparison with renewables given the energy output of $EROI_{ST}$ is a fuel (which is beset with Carnot efficiency losses when used for electricity generation or transportation) whereas the electrical output for renewables is a form with less subsequent losses.

Figure 2. Comparison of $EROI_{POU}$ ratio estimates for different energy sources including power plant / transformational conversion efficiencies



Source: Brockway et al. (2019); Tariq (2019).

Brockway et al. (2019) calls for the widespread adoption of $EROI_{POU}$ and concludes that EROI for many renewables-based technologies may actually now be higher than values for fossil fuel when measured at the same final energy stage, i.e., electricity generation, when ensuing energy conversion losses are similar whatever the source. Their work collates values from previous EROI studies that have adopted the same methodological approach for EROI_{POU}. These values have been used as the basis for

Figure *2*, which has been supplemented with more recent studies from Tariq (2019) for solar PV, and earlier work for additional technologies by Hall et al. (2014).

When comparing the EROIs of fossil fuel and renewables, one clear long-term observation is that EROI values for fossil fuels (and hydroelectric power) are on a steady and irrecoverable decline due to finite and evermore inaccessible resources, whilst those for renewables are steadily rising. The oil and gas industry can be said to have been built on the backs of the early EROIs of 1,000:1, when oil was essentially available ‘on tap’, whilst the renewable energy sector (wind and solar) has faced the far greater challenge of beginning at low levels of EROI (in early stages of development this was sometimes less than one) and improving their EROI. This took place whilst receiving relatively little support and whilst experiencing a significant subsidy imbalance. Olson and Lenzmann (2016) estimates annual global fossil fuel subsidies of between US$ 750 billion and US$ 1,800 billion, compared with US$ 120 billion for renewables. They highlight that this omits environmental and health external costs of fossil fuel use, which they calculate as adding a further US$ 4,800 billion. This is explored in more detail in later sections.

4. Taxes, Subsidies and incentives

Most countries have fiscal policies on energy. They may tax energy to gain revenue, perhaps implement a differential tax to steer energy users in a particular direction, or they may offer tax incentives, grants or subsidies to promote technology, or to support social actions. For example, we have calculated that the financial payback time on externally insulating (cladding) a house in the UK may be unacceptably long at 70 years. If the government offers a grant which reduces the payback time to five years, the owner will probably be inclined to commission the cladding. But is this the right thing to do for society? A more significant metric is to calculate the energy balance; that is, how much embodied energy is in the cladding (manufacture and installation) compared to the energy saved by the additional insulation due to the cladding?

The UK cladding programme is usually to add 100 mm of polyurethane to the external faces of a building.

Table *1* is based on assumptions in order to illustrate the importance of calculating embodied energy. Here we compare polyurethane cladding with glass quilt cladding for 1 m^2 of external wall and calculate the energy saved over one year. The U-value is improved in each case, but the embodied energy in polyurethane is much greater than in glass quilt. However, polyurethane is a superior insulator. To compensate for this, we would need 200 mm thickness of glass quilt to equate to 100 mm of polyurethane. Using these parameters in the first and third columns of Table 1 we can see that the ratio of embodied energy to annual energy saved leads to energy payback periods of 51 years and 11 years respectively. The middle column represents the values for 100 mm of glass quilt and here, although the annual energy saving is less, the energy payback period is only 7 years. Please note that these calculations are sensitive to the assumptions made, and so are only to illustrate the point that energy payback is a valuable decision-making tool. Fiscal interventions may be socially and politically essential or expedient, but energy accounting better represents the impact of our actions on the planet. Grants are often available for the installation of building insulation which may make the cost attractive to the building owner, but on the basis of energy payback polyurethane would be an unwise choice.

Table 1. Energy payback comparison of polyurethane versus glass quilt

Material	**Polyurethane**	**Glass quilt**	**Glass quilt**
Thickness	100 mm	100 mm	200 mm
Embodied energy (MJ/kg)	101.5	28	28
Density (kg/m^3)	30	12	12
Previous U-value (W/m^2K)	1.25	1.25	1.25
New U value (W/m^2K)	0.15	0.3	0.15
Annual energy saved MJ[*]	6	5	6
Embodied energy (MJ)	305	34	67
Energy payback (years)	51	7	11

[*] Assuming an average temperature gradient of 12K (12°C) for 10h/day for 5 coldest months.

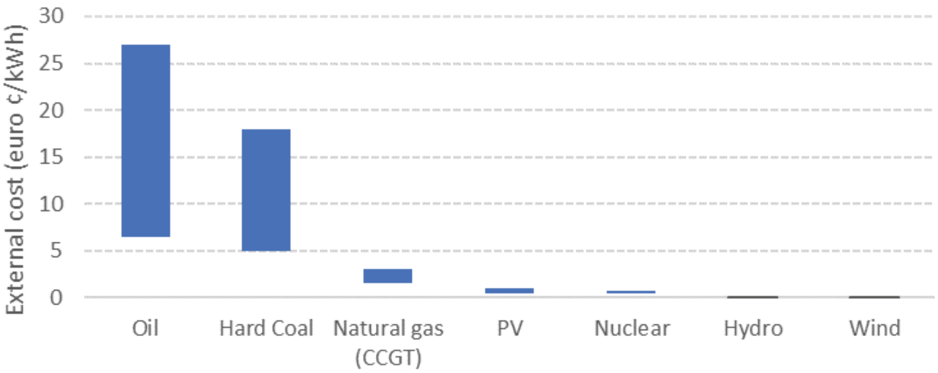
5. Externalities

5.1 The economics of energy

The world trade in energy operates in conventional economics. Oil and gas companies have world-wide exposure and influence. Coal, being a much greater greenhouse gas emitter (per unit of energy) is not preferred for electrical generation, but nonetheless represents an important source of energy or an export commodity for several countries. Once exploited in a country, the energy is subject to national taxes, and these may distort the normal economics, for example by taxing diesel more highly than petrol to discourage diesel consumption. On simple economic cost we have experienced reticence in the use of renewable energy. This simple economic cost is the internal cost and does not account for consumption of a finite resource or for any damage to humans or ecosystems during exploitation (from mining, refining to combustion) of the resource. These externalities should be added to the internal costs to give the total cost. Assessing the external costs of say, gas or wind, is difficult, and the EU established ExternE, a research programme to consider external costs (ExternE 2006). Although the programme was curtailed in 2006 with an update in 2012, the value of external costs of electrical generation deduced by the programme are a valuable guide.

Figure 3 shows the external costs of electrical generation using data adapted from ExternE (2006). Note that for the purposes of this paper we have taken the midpoint values from ExternE. These are in close agreement with the data for coal (14 euro ¢/kWh), oil (17 euro ¢/kWh) and natural gas (4 euro ¢/kWh) reported by the World Nuclear Association (2017), which distinguishes between external costs per se and those attributed to Global Warming, and noted that damage from fossil fuels can be 10% to 350% of production cost (The World Nuclear Association 2017). Simply put: applying external costs could change a decision to choose fossil fuel over renewables if the external costs increase the total cost of fossil fuels beyond that of renewables. In fact, renewable costs have dropped quickly in recent years and in many cases are already competitive on internal cost comparison (Lazard 2020). However, we will explore external costs here as they better represent true costs.

Figure 3. External costs of electricity generation



Source: ExternE (2006).

5.2 Application of external costs

In considering external costs the following headings apply:

Depletion of non-renewable resources: According to Hotelling's theory (Corporate Finance Institute 2021) the depletion of exhaustible resources is considered in the prices of the resources, thus costs of depletion are internal. Hotelling's theory proposes that the only time when holders of non-renewable resources should produce their commodities is when the revenue generated from them can exceed that from other financial instruments, such as investing income from the sale would exceed the future value of the asset.

Environmental impacts: Impacts that are caused by releasing either substances (e.g., fine particles) or energy (noise, radiation, heat) into the environmental media: air, soil and water. The methodology used here is the impact pathway approach.

Global warming impacts: For global warming, two approaches are followed. First, the quantifiable damage is estimated. However, due to large uncertainties and possible gaps, an avoidance cost approach is used as the recommended methodology.

Accidents: Accidents are rare unwanted events in contrast to normal operation. A distinction can be made between impacts to the public and occupational accident risks. Public risks can in principle be assessed by describing the possible accidents, calculating the damage and by multiplying the damage with the probability of the accidents.

Energy security: If unforeseen changes in availability and prices of energy carriers occur, this has impacts, for instance on economic growth.

In modelling the transition from fossil fuel driven electrical generation in Indonesia to fully renewable generation by 2050, Duckers and Hasanah (2020) highlighted the cost benefit. See

Figure *4*, for an illustration of a replacement of fossil fuel plant by wind and solar PV technologies over a 30-year period. That is, by replacing each fossil fuel plant as it is retired Indonesia can reach zero greenhouse gas emissions from its electricity generation sector by 2050. The progress to near zero emissions is shown in Source: ***authors' own research***

Figure 5.
Source: ***authors' own research***

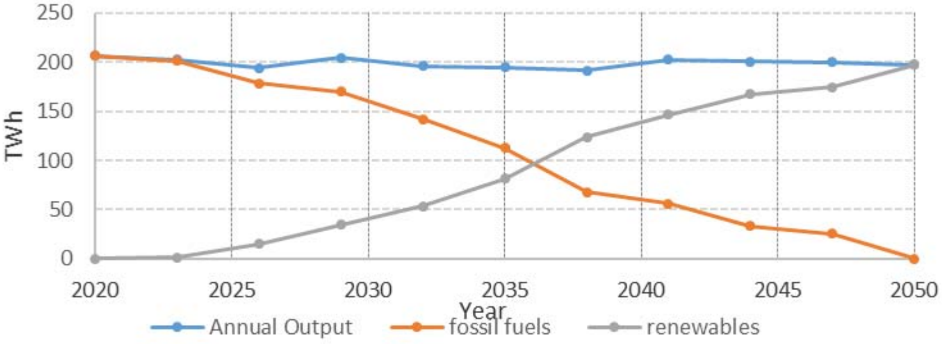
Figure 6 indicates that the unit cost of electricity (internal cost) when executing this transition will actually fall – this is due to the falling cost of renewables when considered in free market terms (Lazard 2018).

If we add external costs to the respective energy generating plants then the unit cost (external + internal cost) is higher as shown in

Source: ***authors' own research***

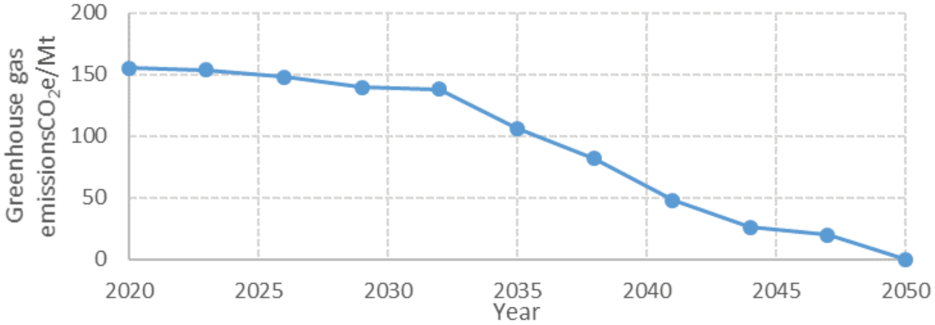
Figure 6, but the advantages of the transition to renewables has a similar trend with time, but now represents total cost. In this case, this offers little extra strength to the case for renewables because the renewables are cheaper in internal cost considerations anyway. Where the renewables have a higher internal cost then the argument should be addressed in total cost terms by including external costs. In fact, in this case the externalities are not absolutely needed to support the argument for a transition to renewable energy. The externalities do, though, help to make the case more strongly and are a better representation of the environmental reality (resources and pollution). Duckers and Hasanah (2020) go on to show that Indonesia will save more carbon dioxide and more money by shortening the zero-emission deadline to 2040 and will save even more my acting to achieve zero greenhouse emissions from its electricity generation sector by 2030.

Figure 4. Annual electricity generation for Indonesia highlighting increase in renewable share as fossil fuel generation is retired



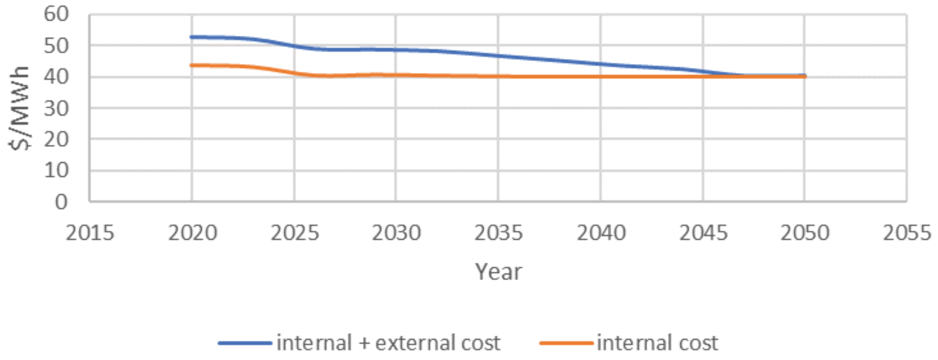
Source: authors' own research

Figure 5. Modelling results of greenhouse gas emissions from Indonesian electricity generation sector as fossil fuel generation is retired



Source: authors' own research

Figure 6. Modelled internal and external electricity cost for Indonesian electricity generation as fossil fuel generation is retired



Source: authors' own research

Citing total cost is not only a more genuine representation of the true cost of energy but will help to encourage decision makers to engage in the programme towards zero-carbon electricity generation.

6. Conclusion

Traditional economics uses the market to set costs, but this fails to take account for the impact beyond the market, such as the impact on health of emissions from internal combustion engines in cars, or the increase in the enhanced greenhouse effect. By taking the full cost as represented by adding the external costs to the internal costs the polluter would actually pay! This would make motoring, for example, more expensive, but on the other hand, health costs would decrease because the amount of fuel used would decline with price, and so damage to health would reduce.

We propose using energy accounting and external costing as rational and essential tools in primary decision-making. If a proposed scheme does not deliver a high return on energy (EROI) then it should not be progressed, and certainly only schemes with a EROI greater than 1 (i.e., a positive energy outcome) should be developed, otherwise they are unnecessarily damaging the planet. External costing gives clear guidance on the impact of a scheme, and in particular provides for a fair environmental comparison between competing options. As the cost of renewable energy schemes decreases, due to improved efficiency and production scales, there is less need to appeal to external costing to assess schemes and convince decision makers. Fiscal interventions to place a scheme into a national framework of aspirations and constraints can be applied after energy accounting has eliminated any irrational environmental options, and optimised the energy return.

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