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Sufficiency or efficiency to achieve lower resource consumption and emissions? The role of the rebound effect

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Abstract

A frequent criticism of eco-efficiency strategies is that an increase in efficiency can be offset by the rebound effect. Sufficiency is discussed as a new strategy involving self-imposed restriction of consumption but can also be subject to the rebound effect. We show that the range of possible secondary effects of efficiency and sufficiency strategies goes beyond the rebound effect. The rebound effect can indeed also be linked to eco-sufficiency strategies but there are further secondary effects of both eco-efficiency and eco-sufficiency strategies, such as double dividend effects. We develop an 'Eco-efficiency-sufficiency matrix' to logically order eco-efficiency and sufficiency measures to attain lower resource consumption and emissions.

Keywords

Eco-efficiency; (eco-)sufficiency; rebound effect; Jevons' paradox

1 Introduction

The absolute reduction of environmental pressures from resource consumption and emissions should be the end goal of eco-efficiency and (more recently defined) eco-sufficiency strategies. Eco-efficiency [1-4] can be put forward as a "win-win" strategy to arrive at a more sustainable use of resources. However it is criticised for its limited ability to lower resource consumption and emissions due to the rebound effect [5-9]. If an increase in efficiency does not reduce resource use then an overall reduction in economic activity is called for. Consequently, more recently eco-sufficiency (see Table 1) has gained attention as a possible alternative to lower environmental pressures through self-imposed restriction of consumption [10-18]. While the rebound effect has previously been primarily discussed in relation to eco-efficiency it is now also linked to eco-sufficiency and the existence of the rebound effect in the context of individual eco-sufficiency has even been called a certainty [14].

TABLE 1 ABOUT HERE

If a reduction in resource use is required for society to become sustainable and neither eco-efficiency increases nor voluntary eco-sufficiency on a micro level can reduce resource use, then an overall reduction of economic activity on the macro level appears to be the ultimate choice. Whether and how this can be achieved democratically is being discussed [16, 19-22]. In this context van Griethuysen [23, p. 595] comes to the conclusion that "aiming at the reduction of the economic throughput and promoting responsible consumption and voluntary simplicity as demand-side alternatives to consumerism, degrowth proposals are unsurprisingly confronted by systematic and systemic discrimination." This hints at substantial changes that would be required to the way our society is organized to make a substantial contribution to a sustainable society.

This article makes two contributions in this context.

Firstly, we argue that the secondary effects of eco-efficiency and eco-sufficiency strategies have been prematurely limited to the rebound effect. Much attention has been given to the rebound effect of eco-efficiency strategies. This article shows that a range of secondary effects, including but not limited to the rebound effect, can occur in the case of eco-efficiency strategies. In contrast to the great interest in eco-efficiency strategies only little attention has been paid to the secondary effects of eco-sufficiency strategies. In particular the attention has concentrated on consumers limiting their own consumption [e.g. 12, 24, 25] with only some very preliminary investigation of eco-sufficiency on the production side [e.g. 26, 27]. This article therefore conducts a systematic analysis of secondary effects of eco-sufficiency strategies on the demand and supply side. It finds that rebound effects occur as well as double sufficiency effects.

Secondly, we show that on the basis of some assumed societal preferences that we make explicit there is a logical order to the strategies society can choose to lower resource consumption and emissions in the presence of the secondary effects that we discuss.

We develop an ‘Eco-efficiency-sufficiency matrix’ to order logically eco-efficiency and sufficiency measures to achieve lower resource consumption and emissions. As we build on, criticize and expand upon existing literature on the rebound effect we also closely follow the typical presentation of the rebound effect. We acknowledge that it is deeply rooted in classical economics. We argue that even from and within the perspective of classical economics the rebound effect is not a certainty as claimed by some [14]. Further criticisms of the existing literature with regards to the assumptions made are of course possible but not subject of this paper.

The article is structured as follows. The next chapter discusses eco-efficiency strategies and shows that a range from double dividend to backfiring effects can be a result of eco-efficiency strategies. The third chapter then moves on to discuss sufficiency strategies, starting with the demand-side analysis of the link between eco-sufficiency and the rebound effect, which is discussed in the literature. In this chapter we then move the debate further to address demand and supply side and the rebound and double sufficiency effect. The findings are then discussed in chapter 4 with the development of our ‘Eco-efficiency-sufficiency matrix’ as a policy decision-making tool. The final section presents the conclusions of this paper.

2 Eco-efficiency strategies

Eco-efficiency reflects the output or return that is created relative to the harm or burden that is caused. A higher return or output and a lower harm or burden is desired. Strategies aiming at a higher eco-efficiency can therefore result in a higher output at a constant burden or a lower burden at a constant output or combinations thereof. These alternatives are dominant and it can therefore be concluded that, if these alternatives can be realized, there is a positive contribution to sustainability as they have a higher performance in one dimension and an at least unchanged performance in the other dimension. Efficiency-driven strategies are quite common in the corporate context and it is therefore not surprising that they are often portrayed as a business contribution to sustainability [2, 28, 29].

However, it has long been argued that there is a risk that eco-efficiency could become a victim of its own success [for example 5, 9, 30]. In other words, there is a risk that increased eco-efficiency leads to increased resource use. In such a situation a ‘rebound effect’ occurs where the additional resources used exceed the resources saved through eco-efficiency. This situation is also referred to as Jevons’ paradox.

Jevons [31] showed among others that the increase of the efficiency of the steam engine between the middle of the 18th and the middle of the 19th century resulted in its increased use. At the time this was primarily considered to be a sign of progress. In Jevons’ words:

"Now, if the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig-iron will fall, but the demand for it increase; and eventually the greater number of furnaces will more than make up for the diminished consumption of each. And if such is not always the result within a single branch, it must be remembered that the progress of any branch of manufacture excites a new activity in most other branches, and leads indirectly, if not directly, to increased inroads upon our seams of coal." [31, p. 124-5]

Today the rebound effect is intensely discussed in energy economics, management and policy [e.g. 6, 32-35] and in a general environment context [e.g. 5, 9, 30, 36, 37]. A reason for this rebound effect could be for example that a higher eco-efficiency has reduced the cost of production, which in turn results in more demand for the good produced and thus more (rather than less) resources being used. A more efficient company might therefore end up using more rather than fewer resources. It can be argued that in such a situation some other mechanism that restricts the total amount of environmental resources used is needed. Figge and Hahn [38] continue this discussion in more detail.

The question whether the rebound effect compensates some, all or even outweighs the reduction gains that can theoretically be attained due to efficiency strategies is of particular interest and intensely debated [e.g. 6, 39, 40-46].

In the following we will discuss two extreme cases of two products that are perfect substitutes and the case of two products that are perfect complements to show that the rebound effect depends on the shape of the indifference curves.

Perfect substitutes

In the case of perfect substitutes the consumer is indifferent about the composition of his or her portfolio of products 1 and 2. This can be the case when both products serve the same purpose. Electricity based on fossil fuels (product 1 in Figure 1) and electricity based on renewable energy (product 2) can serve as an example in this context. From the perspective of the consumer there is no limit to the degree to which one can be substituted by the other. In Figure 1 the indifference curves are therefore straight lines.

Initially consumption takes place at point A, i.e. only product 1 is consumed while there is no consumption of product 2. As a result all of the electricity that is consumed is based on fossil fuels. Analogously to Figure 1 renewable energy now becomes more efficient, which impacts the budget line. With the overall budget more of product 2 and the same amount of product 1 could now be bought.

FIGURE 1 ABOUT HERE

Initially only product 1 was bought. This corresponds to a situation where electricity based on fossil fuels is cheaper than electricity based on renewable energy and therefore preferred by consumers.

Through the increase in efficiency product 2 has now become cheaper than product 1. We discuss once again the substitution and the income effect. Consumption of product 1 is now reduced to zero and consumption of product 2 increases to point B through the substitution effect and further to point C through the income effect. All of the electricity consumed in our example is now based on renewable energy.

There is no income effect of the consumption of product 1 but a substitution effect of product 2 at the expense of product 1. If we assume that the efficiency gain is exclusively due to a more efficient use of energy or environmental resources and that product 2 is more environment-friendly than product 1 then we can conclude that the overall effect on the environment is positive and exceeds the efficiency-induced effect before the income effect is taken into account. After the income effect the overall environmental effect can still exceed the efficiency-induced effect if the positive environmental effect due to substitution exceeds the negative income effect. We refer to this as a double-dividend effect. The efficiency gain results not only in a better environmental performance of product 2 but also of product 1. Under the continued assumption that the efficiency effect is exclusively due to a more efficient use of energy or environmental resources, the positive environmental effect due to substitution will not exceed the negative income effect and the overall effect will therefore still be positive. This is due to the fact that the income effect will at most compensate the positive effect due to the increase of efficiency.

Perfect complements

We now assume that the products are perfect complements. There is for example a complementary relationship, albeit not perfect, between planes and kerosene or household appliances and electricity use. We assume for our example that product 1 is more polluting (e.g. kerosene) than product 2 (e.g. production of planes).

In the case of perfect complementarity two products are used in a given ratio. This is reflected by the indifference curves in Figure 2. An additional unit of one product does not add any utility unless more of the other product is also consumed at the same time.

We assume once again that the efficiency of product 2 increases. In the case of perfect complementarity we observe no substitution but only an income effect. Through the increase in efficiency the slope of the budget line changes. The change in slope of the budget line in isolation does not lead to a change in consumption; points A and B are identical. This is due to the fact that consumption of the two goods must be in a given ratio. There is therefore no substitution of product 1 by product 2.

There is however an income effect. Consumption moves from point A to point C. The efficiency increase of product 2 results in a parallel increase of the consumption of product 1.

Interestingly, for the income effect it does not matter whether product 1 or 2 becomes more efficient. In both cases the consumption of both goods increases to the same degree.

If we continue to assume that the increase in efficiency is due to a more efficient use of energy or environmental resources, then we can conclude that the positive environmental effect due to a higher efficiency of product 2, i.e. the less polluting one, will be more than compensated by the negative environmental consequences of the income effect, i.e. we will observe a backfire effect. We speak of backfire when more environmental resources are used as a result of an efficiency increase [39].

FIGURE 2 ABOUT HERE

As the examples above show an increase of eco-efficiency of one product can have varying effects on the lowering of resource consumption and emissions. The extremes reach from backfiring to results that go beyond the effect that is caused by an increase in eco-efficiency (double dividend effect). Between the two extremes there can of course be a rebound effect to different degrees. The shape of the indifference curves and therefore the relationship between different products play a key role in this context.

The examples above relate to consumption. It can be argued analogously for production. Production factors can be complements or substitutes, which will determine the shape of the isoquants.

The rebound effect is discussed later in this article in the context of eco-sufficiency strategies [14]. A rebound effect occurs in this context when voluntary reduction of resource use is compensated by an increase of resource use by other market actors.

3 Eco-sufficiency strategies

The previous section has shown that there are a range of possible secondary effects of eco-efficiency strategies. Eco-efficiency strategies cannot guarantee lower resource consumption and emissions. Sufficiency is therefore increasingly discussed as a strategy to achieve this [11-17, 26]. At first sight sufficiency strategies appear to guarantee lower resource consumption and emissions. As Alcott [14] shows this is not necessarily the case. A self-imposed restriction of consumption can lead to lower prices, which entices other consumers to consume more, which leads, similar to the efficiency case above, to a rebound effect. While such a sufficiency rebound effect can certainly exist we disagree with Alcott that the sufficiency rebound is a certainty [14, p. 777]. In the following we address two limitations and one imprecision. Alcott concentrates on consumers when discussing sufficiency strategies; we believe that sufficiency strategies must not be restricted to consumers but can also apply to producers. Alcott furthermore concentrates on the existence of a rebound effect. We show that there can even be a double sufficiency effect, i.e. a sufficiency effect that goes beyond the initial reduction associated with following a sufficiency strategy. In the following we discuss all four cases, i.e. demand and supply side with both rebound and double sufficiency effects. Table 2 summarises the underlying rationales of the four cases that are explained in more detail below.

TABLE 2 ABOUT HERE

In our analysis we also correct an imprecision in Alcott's analysis. Alcott uses a classical demand and supply analysis for his analysis and we follow him in this regard. However, Alcott models sufficiency strategies by a parallel translation of the demand curve suggesting that the same quantity will be demanded but at a lower price. We argue that this is not compatible with the idea of sufficiency that proposes an absolute limit irrespective of the price. Put differently, sufficiency presupposes that the additional demand or supply is not a matter of a lower (demand) or higher (supply) price but that the decision to limit demand or supply is taken irrespective of market considerations.

3.1 Demand-side sufficiency rebound effect

In the following the sufficiency rebound effect is shown using a classical analysis based on demand and supply curves. As outlined above, our analysis differs from earlier analyses with regard to the shape of the demand curves. When a consumer follows a sufficiency strategy the demand curve changes. Earlier analysis models this by shifting the demand curve to the left [14]. This does, however, not reflect a sufficiency strategy but rather a lower willingness to pay for a given quantity. Any given quantity can still be attained as long as the price is low enough. In our analysis the demand curve becomes a vertical line at a given quantity. This reflects that the consumer would not demand more than a given quantity whatever the price.
Figure 3 shows our analysis. In this figure there are two consumers or consumer groups (1, 2). Both consumers show the usual demand curves (D_1, D_2), i.e. they demand higher quantities as the price decreases. There is furthermore one supply curve (S_t). The supply curve also has the usual shape, i.e. as the price increases higher quantities are offered. Suppliers are passive, i.e. their behaviour does not change and they do not follow a sufficiency strategy. They are in particular interested in selling higher quantities when the price increases and they will sell less when the price decreases.
Consumer 2 adopts a sufficiency strategy. Above a given quantity the demand curve (D_2’) for this consumer therefore becomes a vertical line. This also has an impact on the total demand curve (D_t). The total demand curve describes the combined demand curves of consumers 1 and 2 and it is this demand curve together with the total supply curve that allows us to

determine the overall price and quantities consumed in the market. We furthermore distinguish between t0 (situation before the sufficiency strategy) and t1 (situation after the sufficiency strategy). We can now observe the following effects.

Before the adoption of the sufficiency strategy by consumer 2 a quantity of Q_t^0 at price P^0 is demanded. This is where total supply (S_t) and demand (D_t) curves intersect. The total quantity of Q_t^0 corresponds to the sum of Q_1^0 and Q_2^0, i.e. the sum of the quantities demanded by consumers 1 and 2. Similar to Alcott we now make the assumption that consumer 2 decides to unilaterally restrict its consumption. We assume, also in line with Alcott, that the consumer decides to work less at the same time, i.e. the consumer reduces its available budget. In principle the quantity demanded goes down from Q_t^0 total to Q_t^{0}'. Q_t^{0}' describes the quantity that would be demanded by all consumers had the price not changed. A reduction of the demand will however also lead to a decrease of the price. The new price (P1) can be found by looking at the intersection of the new total demand curve (D_t') and the supply curve (S_t). At price P^1 a quantity of Q_t^1 is demanded. As can be easily seen the reduction of the total quantity (Q_t^1-Q_t^0) is less than the reduction of quantity demanded by consumer 2 (Q_2^1-Q_2^0). This is due to an increase of quantity demanded by consumer 1. Consumer 1 profits from the lower price and demands a higher quantity (Q_1^1 rather than Q_1^0). Consumer 2 therefore creates a positive externality for consumer 1. This can be considered a typical positive externality as consumer 2 incurs the private cost and consumer 1 benefits from the public benefit. The additional quantity demanded by consumer 1 corresponds to the sufficiency rebound effect.

FIGURE 3 ABOUT HERE

The size of the rebound effect will depend on the shape of the demand and supply curves [14, p. 776]. A lower elasticity of demand of consumer 2 will lead to a larger fall in price when the sufficiency strategy is followed. This will increase the attractiveness for consumer 1 to consume more. By how much the price changes will also depend on the elasticity of supply. The lower the elasticity of supply the higher the price drop as consumer 1 changes the quantity demanded. Finally, the size of the rebound effect will depend on the reaction of consumer 1 to the price changes. Consumer 1 will create the more additional demand the higher his elasticity of demand.

That lower demand leads to lower prices and lower supply on the one hand and an increase of demand by other consumers and thus a higher demand on the other hand is a standard assumption in economics. We find this situation in particular when we have a situation of perfect competition where there are many suppliers and consumers. Commodity markets are a good example here. Commodity markets trade products with little differentiation. A fall in demand of one consumer of a product like gold, orange juice or natural gas that leads to a price drop is likely to be partly or fully compensated by an increase of demand of other consumers. We expect to observe a rebound effect. A unilateral reduction of demand will therefore risk being ineffective on the level of total demand at least in the medium to long term.

3.2 Demand-side double sufficiency effect

The sufficiency rebound effect is only one of several possible effects. To show this point we introduce in the following the demand-side double sufficiency effect. The demand-side double sufficiency effect describes a situation in which the sufficiency strategy of one consumer leads to a reduction in consumption of another consumer. This can for example happen when consumers face a natural monopoly of the suppliers. We conduct an analysis similar to the sufficiency rebound effect. Figure 4 illustrates the situation of the double sufficiency effect. In this figure the supply curve now has a different shape. The supply curve represents a situation in which higher quantities are linked to lower rather than higher marginal costs. This can for example be the case when production is linked to high fixed and low variable costs. In such a case economies of scale exist (almost) indefinitely.

FIGURE 4 ABOUT HERE

We continue to assume that there are two consumers and that consumer 2 follows a sufficiency strategy. As in the previous example this does not only have an impact on the demand function of consumer 2 but also on the total demand function. Before consumer 2 follows a sufficiency strategy there is a demand of Q_t^0 Total at a price of P^0. This is where the total demand curve and the supply curve intersect. What is different in this case here is that when consumer 2 reduces his demand to $Q_2^{1'}$ the price increases rather than decreases. This is due to the fact that a large block of fixed costs must be distributed across a smaller quantity. In contrast to the example above the quantity of $Q_t^{0'}$, i.e. the quantity that would be demanded at an unchanged price, exceeds the quantity of $Q_t^{1'}$, i.e. the quantity that is demanded at the new price. Interestingly, it is not only consumer 2, who makes a contribution to the reduction of the quantity demand. As the price increases consumer 1 also reduces his consumption (Q_1^0 bigger than Q_1^1).

We therefore observe a demand-side double sufficiency effect, which consists of the autonomous reduction in demand of consumer 2 and the price-induced reduction of demand of consumer 1. At first sight this example might sound rather hypothetical. Natural monopolies are however not uncommon for example in the airline industry [47]. Flying an empty plane on a particular route results in only little less costs than flying a full plane on the same route. As the average load factor of the plane decreases the fixed costs must be distributed across a smaller number of passengers. This can result in higher prices and discourage further passengers from flying. A few passengers that decide not to fly on a particular route any more might drive up the price for the remaining passengers, which in turn discourages the remaining passengers to fly on this route, leading to a collapse of the route altogether. Interestingly, when the closure of plane routes is announced insufficient load factors are usually given as a justification. Other examples have in common that they refer to products with high fixed costs of production. Uncongested toll roads, electricity production or hotels are other examples of natural monopolies in this context. A reduction of demand can in these cases drive up prices for all consumers, which can lead to a further reduction of demand.

3.3 Supply-side sufficiency rebound effect

Sufficiency is usually discussed in the context of consumption. It is widely accepted that there are consumers, who – rather than maximising – limit their consumption. Sufficiency strategies must not be limited to consumers but can also extend to the supply side. There is an increasing amount of evidence that there are decision makers, who pursue more than a single objective and are willing to compromise on an economic objective at the benefit of an environmental or social objective. The literature on social entrepreneurship and the role of social issues in SMEs is a good example in this context [see e.g. 48, 49, 50]. Alternatives to the model of economic man are indeed discussed in the literature not only with regards to consumers but also to firms [51]. For the supply side an analysis similar to the analysis for the demand-side can be conducted and due to the analogy this can be done more succinctly.

We now distinguish between two suppliers and a single demand curve. In the supply-side analysis it is now the consumers, who are passive, while supplier 2 is active. Supplier 2 decides to follow a sufficiency strategy. The supply curve will now shape vertically upward at a given quantity. This reflects that the supplier will not offer more of his product after a given quantity regardless of the price offered. We are now interested in the impact this will have on the total supply curve. Analogously to the analysis of the demand side the total supply curve will bend upwards (rather than downwards) from a given point.

FIGURE 5 ABOUT HERE

Figure 5 shows the different effects. Before the implementation of supplier 2's sufficiency strategy a total of Q_t^0 at a price of P^0 is sold. Supplier 2 decides to limit production to $Q_2^{1'}$. This results in an increase of the price to P^1 and a reduction of the total quantity offered to Q_t^1. The reduction from Q_t^0 to Q_t^1 is less than the self-inflicted reduction of supplier 2 (Q_2^0 to $Q_2^{1'}$). This is due to the fact that supplier 1 profits from the price increase and offers Q_1^1 rather than Q_1^0. This constitutes a positive externality from the perspective of supplier 1. We observe a supply-side rebound effect. The reduction of supply of supplier 2 is partially offset by an increase of supply of supplier 1.

The size of the rebound effect will, analogously to the rebound effect on the demand side, depend on the shape of the demand and supply curves. The lower the elasticity of demand and the higher the elasticity of supply of supplier 1 the more pronounced will be the rebound effect.

We would expect to see such an effect in cases that are similar to the demand-side sufficiency rebound effect. Where there is perfect competition on commodity markets we would expect other suppliers to take advantage of a reduction of supply by another supplier. A unilateral reduction of supply will therefore risk being ineffective on the level of total supply. This applies for example to orange juice, natural gas or gold. A unilateral reduction of supply of one of these commodities by one supplier will be replaced by the supply of another supplier.

This effect might not be immediate but will happen over time. The much-cited pork cycle effect [52] is a good example in this context. Suppliers will react to market changes even if it takes some time and might result in temporary under- or overshooting of supply.

3.4 Supply-side double sufficiency effect

In the case of the supply-side effects it is supplier 2 who is active and consumers are passive. Consumers will therefore not work more or less to have the same purchasing power as a reaction to the sufficiency strategy of supplier 2.

The following example will show that there can be a double sufficiency effect as a result of an autonomous reduction of supply by supplier 2. The double sufficiency effect consists on the one hand of an overall reduction of consumption of the good of which supplier 2 reduces the supply and on the other hand of a reduction of the budget that consumers have available after the consumption of this good.

In Figure 6 we see the usual two suppliers 1 and 2 where 2 follows a sufficiency strategy in t1. Demand for this product is less elastic (in absolute terms) than the total supply. By restricting supply of this product the price goes up from P^0 to P^1. Supply of this product by supplier 2 goes down from Q_2^0 to Q_2^1. We observe yet again that supplier 1 will increase production from Q_1^0 to Q_1^1, i.e. we observe a rebound effect. As long as this rebound effect of supplier 1 is less pronounced than the sufficiency effect of supplier 2 we observe a net single sufficiency effect. This is the case here as Q_t^0 exceeds Q_t^1.

Due to the inelastic demand the prices increase drastically. This leads to the second sufficiency effect. At t0 consumers spend a total budget of $P^0 * Q_t^0$ on this product. After the reduction of supply the budget increases as consumers must now spend $P^1 * Q_t^1$. The additional budget, i.e. $P^1 * Q_t^1 - P^0 * Q_t^0$, cannot be spent on other products and the sufficiency strategy of supplier 2 will therefore lead to a reduction of the consumption of other products.

FIGURE 6 ABOUT HERE

At this stage and without an analysis of the demand for other products we can only say that the budget that is available for other products will be reduced. The demand for which products will be reduced will depend on the shape of the individual demand curves.

We expect this effect to occur whenever the demand for and the supply of a product is very inelastic. In such a case reductions of supply will lead to higher prices even in the long run and will require consumers to spend a higher proportion of their budget on that product at the expense of the consumption of other products.

Veblen [53] and Giffen [54] goods are extreme examples in this context. In the case of these goods demand even increases as prices go up. In the case of Veblen goods they become more attractive as they become more expensive. This can be the case of luxury products that are considered to be more exclusive as they become more expensive. Giffen goods are consumed more as their prices increases as they remain the cheapest way of satisfying a basic need and will therefore not be substituted by other goods despite the higher price. Fossil fuels for heating purposes can serve as an example here. Heating houses is a basic need. As fuel prices go up the money spent on fossil fuels at an unchanged or even lower consumption of fossil fuels increases. Other fuels are even more expensive. Consumers therefore have no choice but to increase the share of their budget they spend on fossil fuels and to decrease the consumption of other products. This is also being discussed as the problem of fuel poverty [55].

4 Prioritising eco-efficiency and sufficiency strategies for lower resource consumption and emissions

The fundamental premise of this paper is that lowering resource consumption and emissions is the broad societal aim when eco-efficiency and eco-sufficiency strategies are promoted and implemented. As shown above neither eco-efficiency strategies nor eco-sufficiency strategies can guarantee lower resource consumption and emissions. However, the picture is not as bleak as it is sometimes painted. Neither eco-efficiency nor eco-sufficiency will necessarily result in a rebound effect. The challenge is to prioritize eco-efficiency and eco-sufficiency strategies to aid decision-making on environmental policy that needs to balance economic growth and lower resource consumption and emissions such as greenhouse gases [56].

In our 'Eco-efficiency-sufficiency matrix' in Figure 7 we start by addressing this challenge by bringing eco-efficiency, eco-sufficiency and other forms of collective restraint into a logical order. This Figure illustrates the logic of the relationship, which exists between eco-efficiency and eco-sufficiency in the pursuit of lower resource consumption and emissions.

FIGURE 7 ABOUT HERE

The figure reflects two sets of normative assumptions that we make.

On the one hand we assume that anything that does not require any restraint, i.e. any kind of optimisation, is preferred to restraint and that individual restraint is preferred to collective restraint. An eco-efficiency strategy that allows producing the same output with fewer resources would be an example for an optimisation that does not require any restraint. This reflects an individualistic worldview, i.e. that actions taken voluntarily by individuals are preferred to decisions that are imposed collectively.

On the other hand we assume that anything that preserves utility is better than something that reduces utility. An eco-efficiency strategy that produces a higher output at a constant resource use would be an example of a strategy that is preferred to a strategy that reduces output to keep resource use constant. This can be considered obvious as it follows the standard assumption that a higher utility is preferred to a lower utility.

Eco-efficiency increases the ratio of desired output to undesired resource use. By increasing eco-efficiency the use of resources is optimised. Eco-efficiency can deliver reductions whenever the increase of eco-efficiency is not outstripped by the growth of demand. Eco-efficiency strategies then have the potential to reduce the burden on the environment at no cost, i.e. not requiring any restraint. Eco-efficiency strategies are therefore a first priority. Where eco-efficiency strategies do not deliver reductions, some kind of restraint is necessary. We now distinguish between four cases of restraint.

The first case is individual eco-sufficiency. It is based on the voluntary decision of a single decision maker to reduce his or her resource consumption such as electricity use knowing that it will entail a net-reduction of his utility. This frees up resources at a net cost to the decision-maker. These resources can be used by another decision-maker, which leads to a rebound effect.

The second case is collective restraint to counter the rebound effect of individual eco-sufficiency. This is for example the case when emissions are reduced by an individual decision maker and the equivalent amount of emission permits are taken from the market. This is to make sure that the resources saved through the eco-sufficiency of a single decision-maker are not used by another decision-maker. It ensures that the lower resource consumption and emissions intended by the decision-maker on the individual level is also reached on the societal level. The overall resource use of the other decision-makers does not change and there is therefore no loss of utility of other decision-makers compared to the initial situation, i.e. prior to the eco-sufficiency initiative of one decision-maker, who bears the full cost.

The third case takes into consideration that a widely recognized reason for environmental degradation is the existence of externalities. Externalities occur when the cost and the benefit of a decision are not borne by the same decision-maker. The relevant consequence in this context "is not that one person pays for what someone else gets but that nobody pays and nobody gets, even though the good is worth more than it would cost to produce" [57, p. 278]. In the presence of externalities society therefore risks to attain a suboptimal level of utility. In the environmental context it is usually assumed that too many resources are used due to externalities. Collective restraint in the form of a Pigouvian tax [58], the assignment of property rights [59] or command and control measures are therefore the third case. They make sure that the societal optimum, i.e. a higher level of utility is reached. This higher utility on the societal level can come at a net-cost to individual decision-makers.

A fourth case is a collective commitment to eco-sufficiency such as an individual carbon budget within a capped societal budget. Following the definition of eco-sufficiency above and in analogy to individual eco-sufficiency there will be a net loss of utility.

Case one is preferred to the other cases as it reflects our preference of individual over collective restraint. Case two is preferred over cases three and four as it comes at no cost to the collectivity. Case three is preferred to case four as it increases or at least preserves utility on the societal level. The fourth case will come at a net cost to society.

We can now bring eco-efficiency, eco-sufficiency and other forms of collective restraint into a logical order as outlined in our 'Eco-efficiency-sufficiency matrix' in Figure 7. This figure illustrates the logic of the relationship, which exists between eco-efficiency and eco-sufficiency in the pursuit of reductions. If any of the individual actions, e.g. eco-efficiency, is enough to achieve reductions then no further action is required. However, where reductions are not achieved or the rebound effect reaches a threshold at which it outweighs the initial action the next step is required. Whether the disutility of eco-sufficiency strategies is justified in the light of the possible environmental benefits is a separate question.

Hence our ‘Eco-efficiency-sufficiency matrix’ could be used to inform policy decision-making to maximize the potential for lower resource consumption and emissions by avoiding the rebound effect. This can be incorporated into existing policy assessments, e.g. the UK Government ‘Sustainable Development Specific Impact Test’ [60]: “The role of the Sustainable Development Specific Impact Test is to enable government departments conducting policy appraisal to identify key impacts of their policy options relevant to sustainable development and to give informed advice to ministers on sustainability-related issues.” The matrix is a simple method to logically work through where a particular policy has rebound effects and how these can be eliminated.

5 Conclusions

Eco-efficiency and eco-sufficiency strategies are frequently discussed as possible contributions to lower resource consumption and emissions. This article has aimed to provide a thorough analysis of the relationship of eco-efficiency and eco-sufficiency in the pursuit of lower resource consumption and emissions from both the supply- and demand-side. This article shows that both eco-efficiency and eco-sufficiency can be linked to the rebound effect but that this is not a certainty. It does become clear though that the link between eco-efficiency and eco-sufficiency strategies in our ‘Eco-efficiency-sufficiency matrix’ cannot be assessed in isolation but must take into account the reaction of other market participants.

An interesting question in this context is whether eco-efficiency strategies or eco-sufficiency strategies should be preferred in a given situation. We interpret the rebound effect as positive externalities from the perspective of other market participants. This allows us to distinguish different levels of societal restraint. Based on an individualistic and utilitarian worldview we can then prioritize eco-efficiency and eco-sufficiency strategies. On this basis we can determine which sufficiency strategy should be chosen *when* sufficiency strategies are taken. A limitation of this article is that this does not tell us, *if* sufficiency strategies should be taken. Again following a utilitarian perspective, to be able to take this decision the environmental benefit would have to be compared to the disutility of the sufficiency strategy. Further research on how to deal with this trade-off is urgently needed. While cause and effects of sufficiency strategies are difficult to establish under real world conditions it would nevertheless be most insightful to see empirical studies on the impact of eco-sufficiency strategies on resource consumption and emissions.

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Eco-efficiency	• The ratio between value created and resources used or impacts created. Eco-efficiency as an indicator is therefore a relative indicator. • "Eco-efficiency strategies focus on maintaining or increasing the value of economic output while simultaneously decreasing the impact of economic activity upon ecological systems. Zero emission, as the ultimate extension of eco-efficiency, aims to provide maximal economic value with zero adverse ecological impact -a true decoupling of the relationship between economy and ecology" [53, p. 1337]. • We distinguish between two basic eco-efficiency strategies; reduction and substitution. By reducing resource use per unit of value created eco-efficiency is increased. Alternatively companies can aim to substitute more harmful with less harmful substances per unit of value created to increase eco-efficiency.
Eco-sufficiency	• The concept of sufficiency is primarily concerned with the reduction of consumption and 'living well on less'. So, in essence where eco-efficiency is concerned with production based on using fewer resources, eco-sufficiency follows the premise that we should limit what is produced or consumed in absolute terms. • "The costs of non-consumption that are voluntarily traded for the benefits of believing one is relieving human pressure on planetary resources and thus benefiting other (present or future) humans or other species" [14, p. 771]. Eco-sufficiency will therefore always encompass some kind of loss of utility or welfare. • Alcott's position relates primarily to the individual consumer, we extend this definition to incorporate the full spectrum of consumption to production, encompassing the individual to the company.

Table 1: Definitions of key terms

	Demand side	Supply side
Rebound effect	Lower demand leading to lower prices, resulting in more demand by other consumers (3.1)	Lower supply leading to higher prices, resulting in an increased supply of other producers (3.3)
Double Eco-sufficiency effect	Lower demand leading to higher prices for and lower demand of remaining consumers (3.2)	Lower supply leading to a price increase, resulting in a reduction of the purchasing power of consumers, decreasing overall consumption (3.4)

Table 2: Rebound and sufficiency effects from a demand and supply perspective

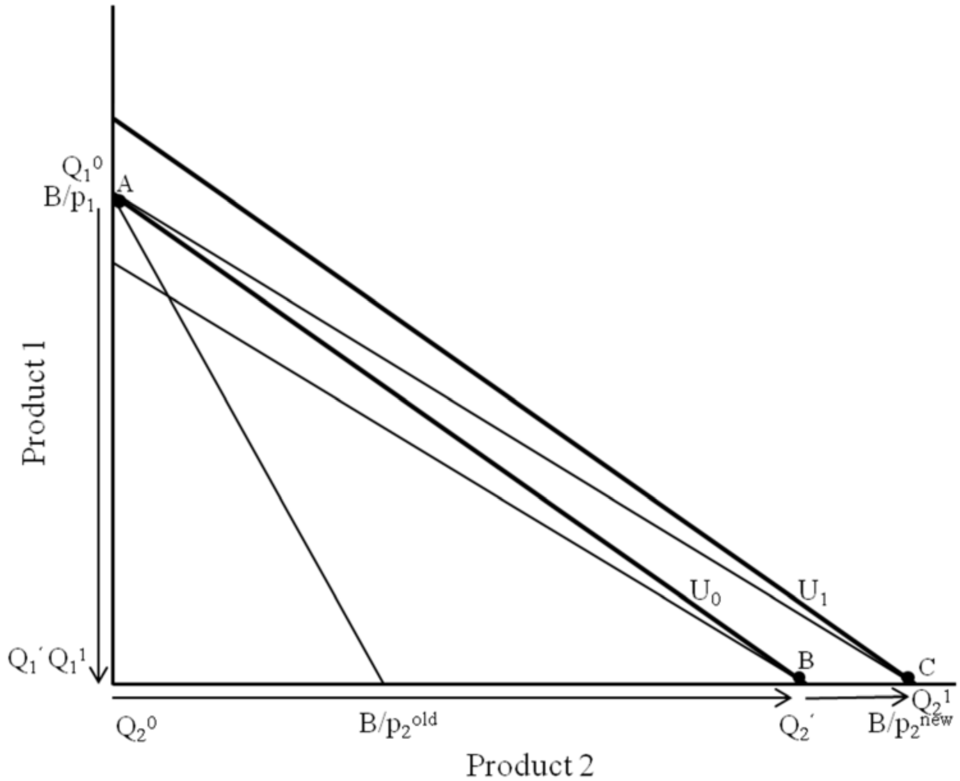

Figure 1: Efficiency and the rebound effect (perfect substitutes)

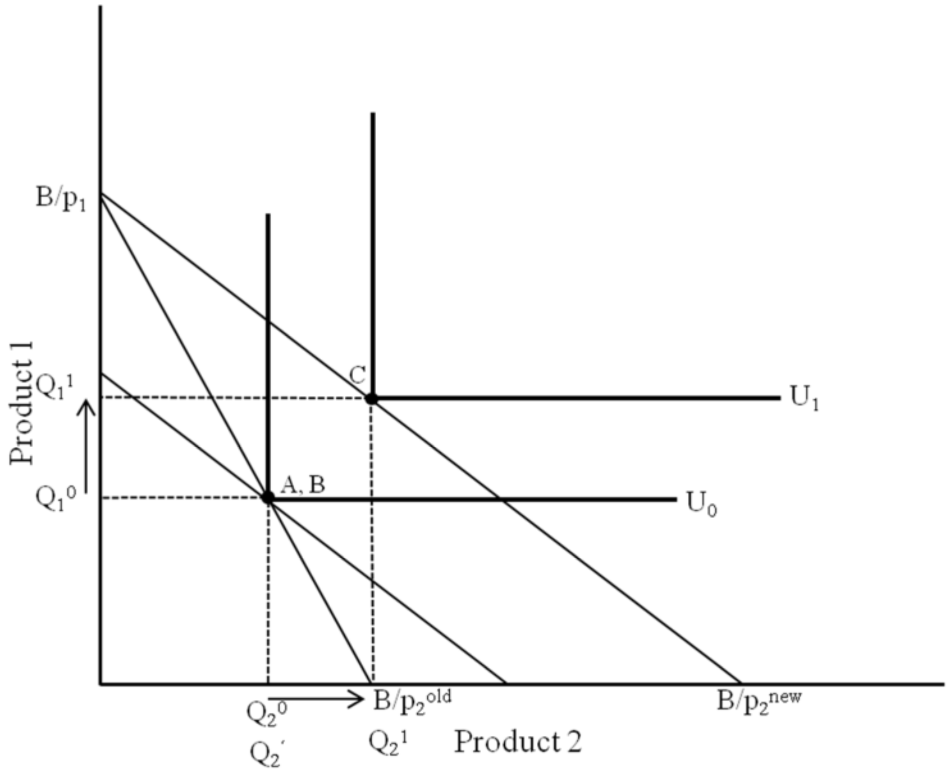

Figure 2: Efficiency and the rebound effect (perfect complements)

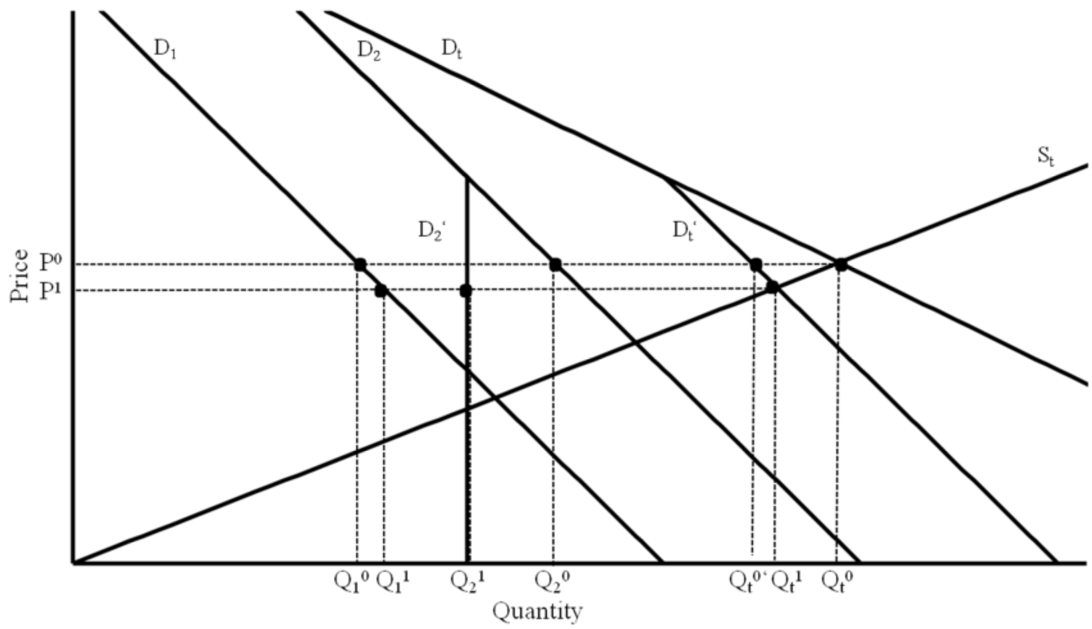

Figure 3: Demand-side sufficiency rebound effect

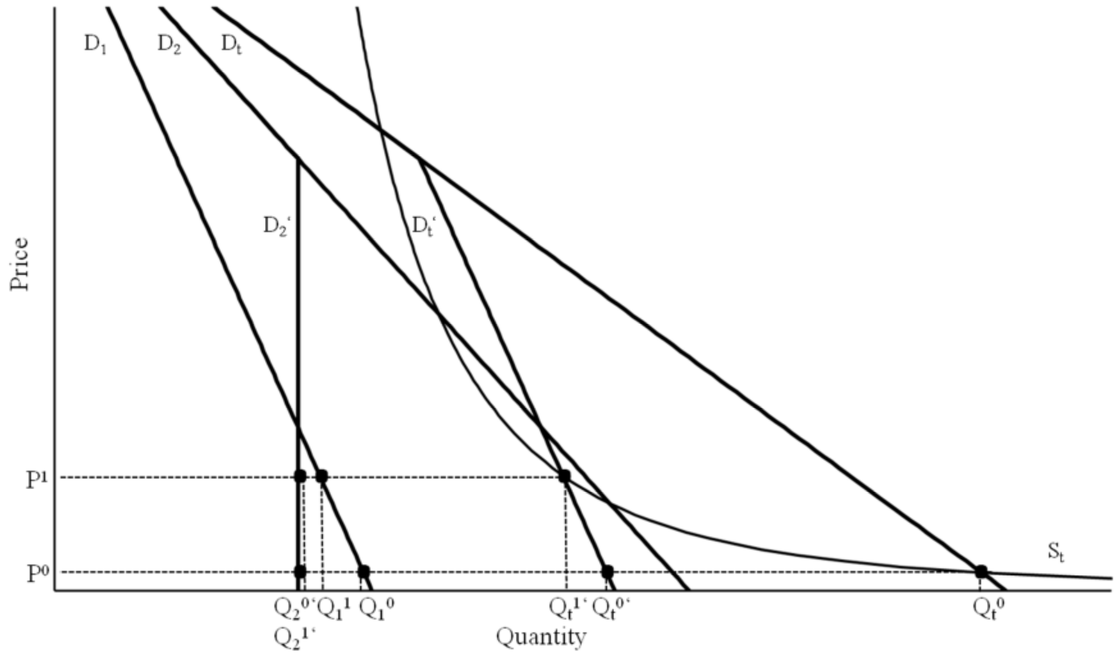

Figure 4: Demand-side double sufficiency effect

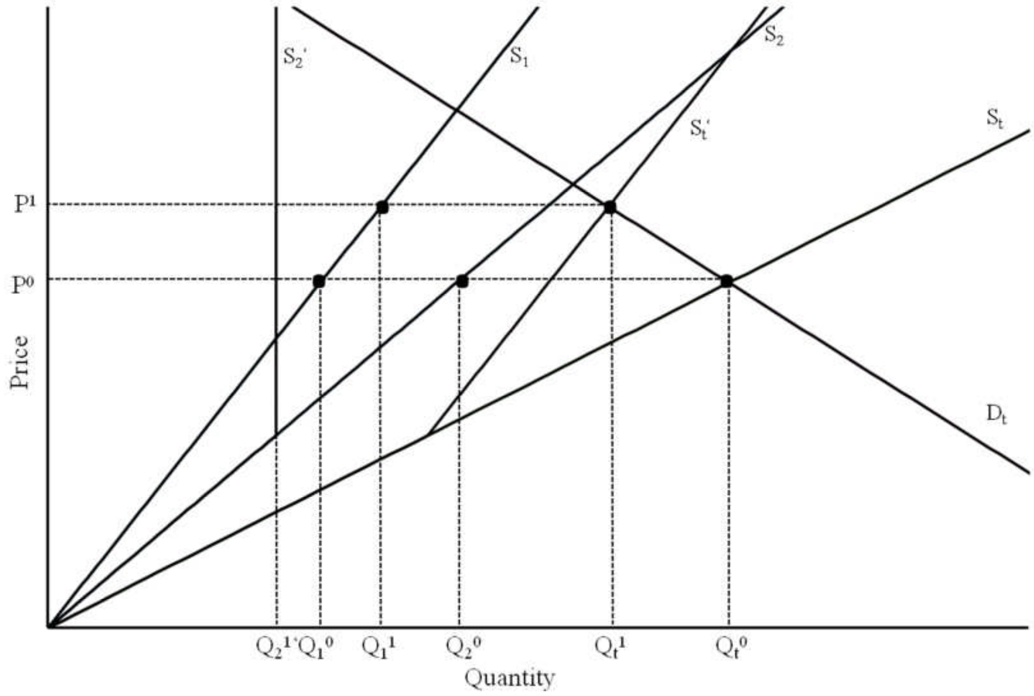

Figure 5: Supply-side sufficiency rebound effect

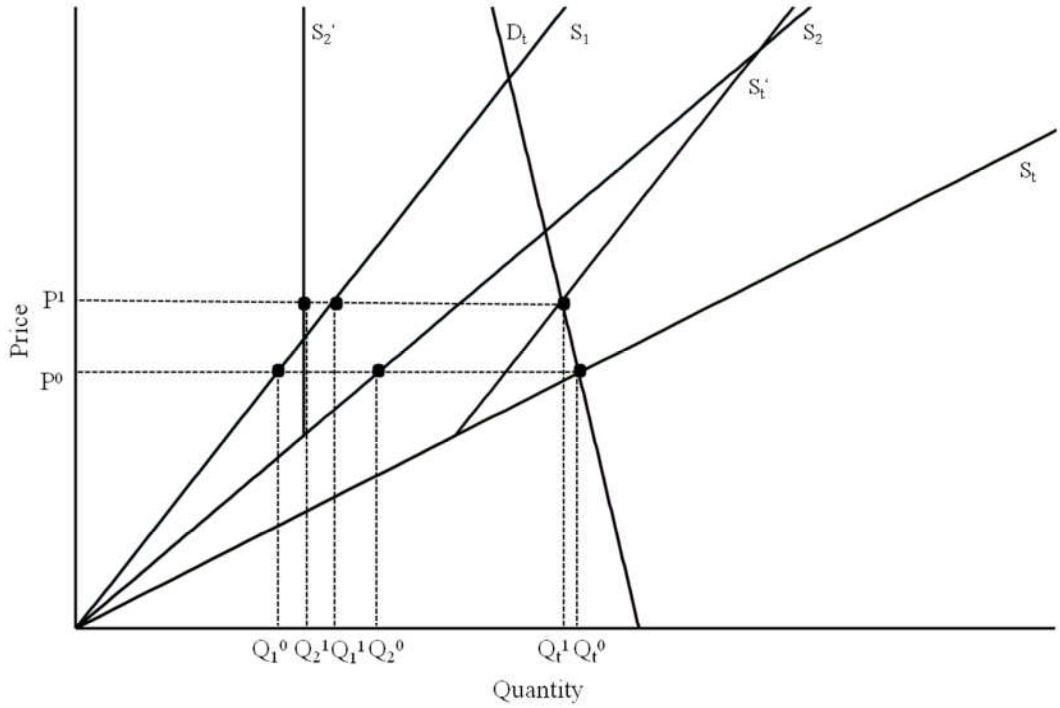

Figure 6: Supply-side double sufficiency effect

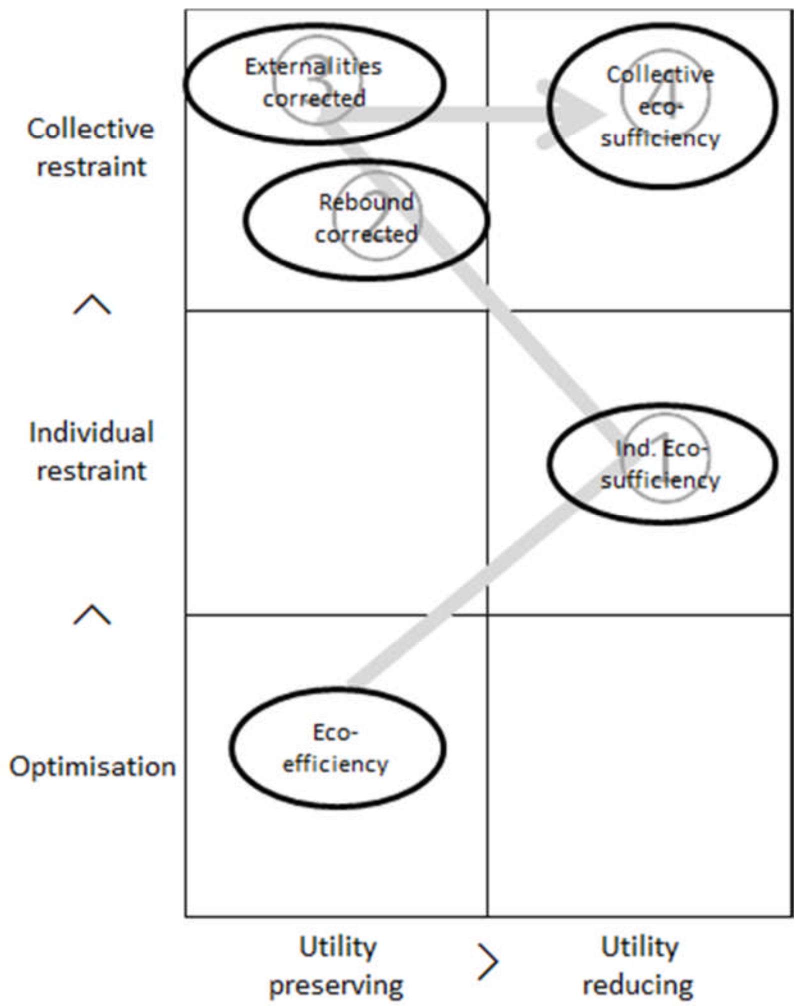

Figure 7: Eco-efficiency-sufficiency matrix