Using System Archetypes to Understand Rebound Effect

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Abstract

Efforts to improve efficiency and promote circular economy have not been successful in addressing natural resource depletion and environmental issues due to the rebound effect (RE). RE occurs at micro- and macroeconomic scales and has been explained by various economic, ecological, and social theories. However, a holistic view is necessary for sustainable solutions. System dynamics (SD) is a suitable tool for this purpose, but studies that examine the nexus between different sectors and encompass various RE theories are still lacking. This study uses system archetypes to scrutinize the RE and proposes a model for future research.

Keywords: Rebound effect, system dynamics, archetype, system molecules

Introduction

The increase in population, changes in consumption patterns, and competition of governments for economic growth have caused severe natural resource depletion and environmental problems [1]. Efficiency improvement and circular economy are usually advised as policy instruments to tackle these issues [2] and ensure sustainable consumption and production patterns (SDG 12) [3]. the solutions have not yielded the expected outcomes due to the rebound effect (RE) [4,5]. The RE refers to an economic or behavioral response that induces more demand and offsets the effectiveness of an action taken to reduce a good or service consumption [6,7]. The measure's benefits may even be negative when the rebound effect exceeds 100% (backfire effect) [8]. The RE manifests in micro-economic (direct and indirect effects) and macroeconomic scale (market price, composition, and economic growth effects) [9], in different disciplines like housing [10], nutrition [11,12], mobility [13], and consumables [14].

Previously, economic theories dominated the research on rebound effects, explaining RE by economic factors like prices, income, and price elasticity [15]. In recent years, however, energy economics, ecological economics, socio-psychological, and socio-technological perspectives [16-18] have offered alternative theories. In addition to the hypotheses, opinions regarding the magnitude of RE [19] and the policies suggested for controlling it are very diverse [20]. For instance, Roadmap to a Resource Efficient Europe [21] describes thirty-six policy areas according to four sectors (energy, food, buildings, and mobility) and nine resources (fossil fuels, materials and minerals, water, air, land, soils, biodiversity, marine resources, and waste). Various methods have been employed to understand RE better and test policies, e.g., econometric tools [22], discrete-continuous [23], ABM [24], and system dynamics (SD).

Most SD-RE studies are related to the transportation sector. To name some examples, Hilty et al. [25] consider direct, indirect, and time rebound effects to investigate how information and communication technology (ICT) may affect the passenger transport demand and modal split. Erdmann & Hilty [26] analyzed different scenarios of the future impacts of ICT applications on GHG emissions. Stepp et al. [27] offered a qualitative model to understand the direct and indirect effects of GHG reduction policies on the transportation sector. Besides direct, indirect, and time rebound effects, Peeters [28] considers "environmental attitude" affecting investment in energy efficiency-enhancing technology and investigates how pollution-saving technologies affect the tourist transport demand and greenhouse gas emissions. Regarding the case of India, Menon & Mahanty [29] test four alternative energy policies (carbon tax imposition, car sharing, car scrappage, and a combination of all of these) in conjunction with the energy efficiency improvement policy to assess which are more effective. Yim [30] analyzes the rebound mechanisms from the improved automobile fuel efficiency based on integrating the economic and social practice theories.

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	Yim (2019)	analyzes the rebound mechanisms from the improved automobile fuel efficiency based on integrating the economic and social practice theories
waste management	Dace et al. (2014)	analyze the policy mechanisms that promote packaging material efficiency in products through increased recycling rates. They show an increasing share of cheaper recycled materials can lead to an increase in the total consumption of packaging materials.
	Freeman (2018)	proposes a qualitative model for the rebound effect at the macro level, based on the concepts of natural capital, the Global Ecological Footprint, and the Great Acceleration. The model represents the flows of energy and material resources and waste between stocks of natural capital, human-created capital, and waste. It considers four types of rebound effects (economy-wide effects, transformational effects, frontier effects, and international rebound effects). It concluded that the magnitude of the rebound effect and the type of impacts it causes would be affected by future changes in the system within which it arises.
household energy consumption	Fazeli & Davidsdottir (2015)	captures the effects of building aging on total Danish energy consumption for space heating demand.
	Fazeli & Davidsdottir (2016)	develop a framework to enhance understanding of consumer behavior by studying the correlation between the rebound effect and the household income for five household categories.
	Zimmermann et al. (2016)	propose an SD model of occupants' decisions and socio-technical interaction with heating and cooling their dwellings.

SD is also rarely applied to study the macroeconomic rebound effect and RE in waste management and household energy consumption. For example, Freeman [31] proposes a qualitative model for the rebound effect at the macro level, based on the concepts of natural capital, the Global Ecological Footprint, and the Great Acceleration. The model represents the flows of energy and material resources and waste between stocks of natural capital, human-created capital, and waste. It considers four types of rebound effects (economy-wide effects, transformational effects, frontier effects, and international rebound effects). It concluded that the magnitude of the rebound effect and the type of impacts it causes would be affected by future changes in the system within which it arises. Dace et al. [32] analyze the policy mechanisms that promote packaging material efficiency in products through increased recycling rates. They show an increasing share of cheaper recycled materials can lead to an increase in the total consumption of packaging materials. Fazeli & Davidsdottir [33] captures the effects of building aging on total Danish energy consumption for space heating demand. Fazeli & Davidsdottir [34] develop a framework to enhance understanding of consumer behavior by studying the correlation between the rebound effect and the household income for five household categories. Zimmermann et al. [35] propose an SD model of occupants' decisions and socio-technical interaction with heating and cooling their dwellings. In short, reviewing SD-RE literature shows that SD studies regarding the nexus between different sectors and studies that encompass different theories and perspectives for RE are still lacking.

In this research, it has been tried to use molecules to build and explain the model. Molecules are small pieces of model structure, encapsulating expert knowledge, which can be combined to gather to form complete models [36]. In this paper, molecule means not only parent-child molecules that are presented by Hines et al[1], but also archetypes, generic models and even models whose validity has already been checked. As an analogy, using molecules for building a simulation model is similar to using building blocks and pre-fabricated components to build a house. Using molecules can enhance the quality and speed of the modelling process in four ways: (1) model conceptualization is the most difficult system dynamics skills to acquire [37]. The isomorphic properties of molecules can be helpful to start starting the model conceptualization activity by transferring insights from other models. (2) Molecules provide cognitive support and better understanding about where your model are coming from and what are the components of the system. There is a proverb that says how to eat an elephant? And the answer is "one bite at a time". Human brain suffers from limitation capacity for processing information and analyzing complex systems. Understanding large and complex models for the human brain is like eating an elephant. Using molecules breaks the model down into digestible and understandable pieces, and as a result, others and even ourselves communicate better with the model. (3) It is important to recognize that system archetypes are first and foremost a communications device to share dynamic insights [38]. System archetypes can serve as a simple, visual representation of a problem to facilitate communication among a team about solutions. (4) System archetypes can be used as a tool to introduce SD. System archetypes can be useful to introduce basic concepts of system dynamics to others because they may provide language for and visual representation of problems that people have experienced and intuitively understand (*especially important in group model building).*

In the following, first, all types of direct and indirect rebound effects are explained, then we focus on "output" and "re-spending" rebound effect, present a SD model, and explain the model through system archetypes of "limits to growth", "attractiveness principle", "fixes that fail", and "shifting the burden". We also benefit from generic models of "market growth", "invisible hand", and "material flow" to build the model.

[1] https://sdmolecules.org/

Conceptual Model

Metic & Pigosso [39] mention seven mechanisms for direct RE (price, income, output, motivational, time, sufficiency, and symbiotic) and six mechanisms for indirect RE (re-spending, re-investing, substitution, consumption accumulation, imperfect substitution, and motivational). These mechanisms are briefly explained in Table 1 and Table 2.

Direct Rebound Effect		
1	Price	Efficiency improvements may reduce the production costs of a product/service, resulting in lower costs and higher demand for the product/ service, which in turn results in higher resource demand for production
2	Income	Efficiency improvements may reduce the total cost of ownership of a product/ service, which in turn results in an increased disposable income and ultimately in more consumption of that product/service
3	**Output**	**Cost savings due to more efficient production can result in an increase in the company's profit, which can be used to further the production of that product/ service and therefore, in more resource consumption**
4	Motivational	As a product/service gets more efficient, consumers' preferences, perceptions and behavior change leading to an increase in the consumption of that product/ service
5	Time	• If customers can consume a product or a service in less time, they are more likely to consume more of it leading to higher resource use • If producers can produce a product in less time, they are more likely to produce more of it leading to higher resource use
6	Sufficiency	• A self-imposed sufficiency strategy of one consumer can lead to lower market prices, being offset by higher consumption of the same product/service by other consumers • Implementation of sufficiency strategies by one producer (i.e., the company does not offer more of its product/service) can possibly be offset by an increase in supply from another producer
7	Symbiotic	The decision of choosing a circular strategy (e.g., reuse over recycling) causes a change in resource flows within a circular system and within producer-producer relationships. The value created from doing one comes at a cost of not doing the other, due to opportunity costs that arise causing a higher-than-expected use of the same resources

Table 1: seven mechanisms for direct rebound effect

Indirect Rebound Effect		
1	**Re-spending**	**Efficiency improvements can reduce the cost of a product/ service and therefore increase the disposable income of a consumer which further can be spent on other products/ services**
2	Re-investing	Efficiency improvement can reduce production costs, consequentially increasing the profit, which in turn can result in re-investing in other production factors
3	Substitution	• Due to efficiency improvement and reduced cost of a particular product/service, consumers will possibly substitute towards consuming those products/services rather than others with lower resource consumption • Due to the efficiency improvement, relative resource and other production input shares could change in response to changes in their relative costs, leading to higher consumption of other resources
4	Consumption accumulation	The demand/supply of more efficient products/services often does not replace but instead supplements conventional products
5	Imperfect substitution	Secondary resources may be insufficient substitutes for primary resources as they are of inferior quality or are otherwise less desirable
6	Motivational	As product/service gets more efficient, consumers' preferences, perception and behavior change leading to an increase in consumption of other products/services

Table 2: Six mechanisms of indirect rebound effect

The focus of this study on direct rebound effect of "output", and the indirect rebound effect of "re-spending". This is an ongoing study and later other mechanisms will add to the model. According to the output mechanism, cost savings due to more efficient production can increase the company's profit, which can be used to further the production of that product/ service and, therefore, in more resource consumption. Based on "re-spending" mechanism, efficiency improvements can reduce the cost of a product/ service and therefore increase the disposable income of a consumer, which further can be spent on other products/ services. To build the conceptual model, we tried to involve four six disciplines of Energy Economics (EN), Ecological Economics (EC), Socio-psychological/Socio-technological (SO), Sustainability and Industrial Ecology (SU), and Circular Economy (CE) (for detailed explanation please refer to Metic & Pigosso [39]).

Stock and Flow Diagram

As mentioned, rebound effect can happen in housing, nutrition, mobility, and consumables. For simplicity, we have aggregated some of these items and instead of individual items that people can spend their money on, we have aggregated them and brought them in the form of two variables: energy (which includes fuel for transportation, energy for heating and cooling, etc.) and GS (goods and ser services) which includes all consumable goods (food, clothing, etc.), non-consumable goods (housing, cars, etc.) and services (travel, etc.). The model consists of 12 sectors and since showing the whole model in one frame would make the words unreadable, the model is sperated in two parts (Figure 1 and Figure 2). The variables that are displayed outside the sectors in each section are endogenous variables in the other part. More precisely, in Figure 1, "supply of fossil fuel-based energy", "energy consumption per GS" and stocks of "perceived environmental side effects by people/authorities/producers", "renewable energy production capacity", and "GS production capacity" are shown outside the sectors and exogenously, while all these variables are endogenous in Figure 2. Also in Figure 2, the stocks of "energy price" and "GS price" are shown as exogenous and outside the sectors, while they are endogenous in Figure 1, an in this way Figure 1 and Figure 2 are connetcted.

In the "Individuals' consumption pattern" sector (Figure 1), GS and energy consumption pattern of individuals have been seen. The pattern of energy consumption depends on people's financial situation, energy price, energy price elasticity, minimum possible energy consumption, energy efficiency, and people's perception about the environmental effects of energy use. Similarly, the GS consumption pattern depends on people's financial situation, GS price, GS price elasticity, minimum possible GS consumption, and people's perception about the environmental effects of GS consumption. As can be seen, the pattern of energy consumption and GS both depend on people's financial resources, and financial resources are a kind of a "limit to growth" for energy consumption and GS. If the money spent for one decreases, this money can be used for another (re-spending RE). For example, if the money spent on the use of energy decreases due to a decrease in the price of energy or a decrease in consumption (due to an increase in productivity), the money in the hands of the consumers will increase, and if people's consumption is not limited, this money can be spent on using more energy or buying more GS. This mechanism is in a way a "fixes that fail" archetype and by increasing energy efficiency (fix), energy consumption or GS can increase (fial).

In the model, the price of GS and energy is determined by the supply and demand mechanism, and of course the government may intervene for environmental reasons and try to control consumption by raising taxes for energy or GS (Figure 1). The total energy demand is equal to the energy consumed by families (population * Individuals' Energy Consumption Pattern) plus the energy used to produce goods and provide services (energy consumed per GS * total GS supply). The energy supply is equal to the total supply of fossil-based energy and new energy (the mechanism of energy transition is included in Figure 2). The total demand of GS is equal to indivuals' consumption pattern times population, and the total supply of GS is also a function of Production capacity (which is mentioned in the second part of the model (Figure 2) and we will discuss it further.

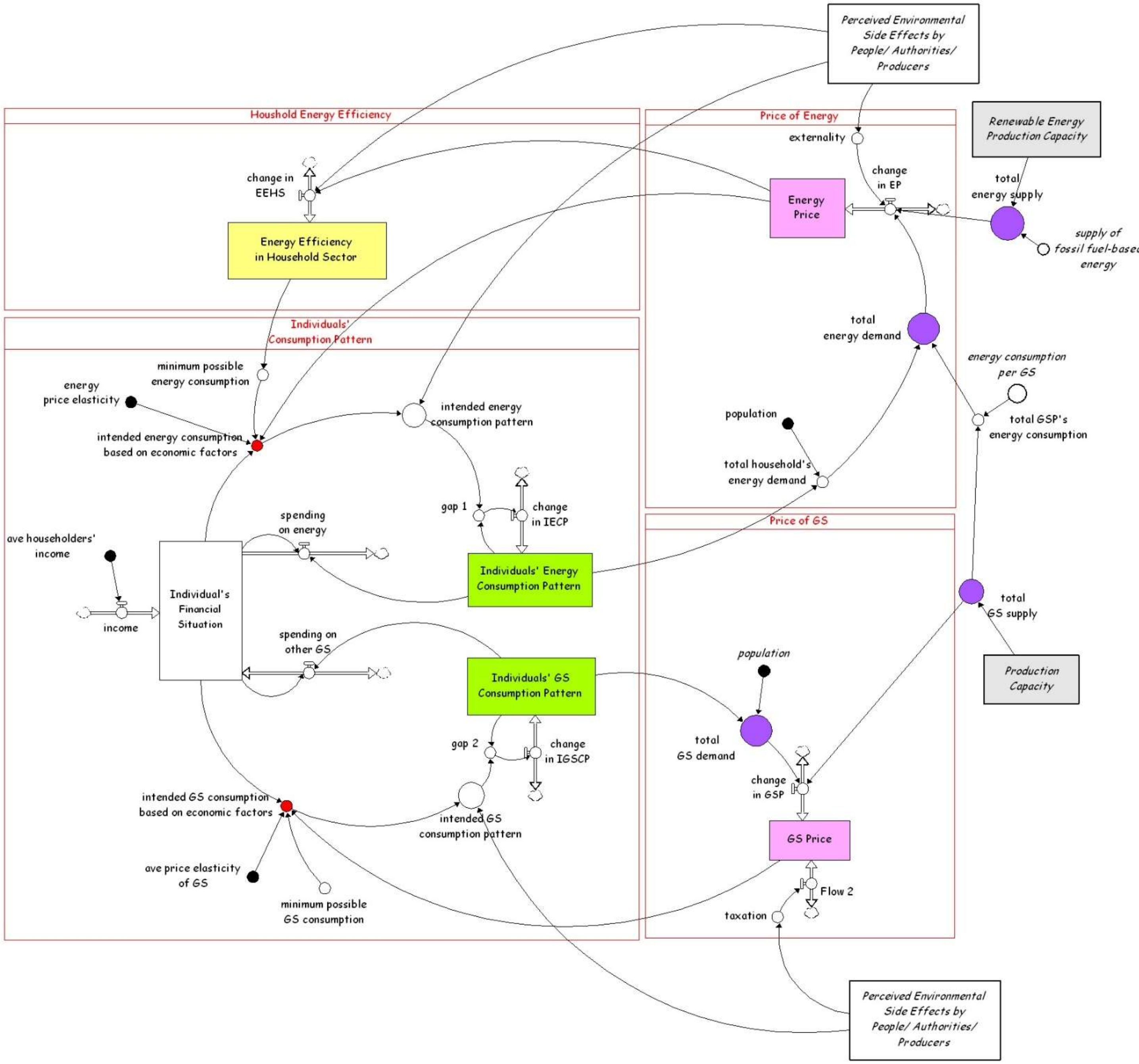

Figure 1: Part 1 of the model

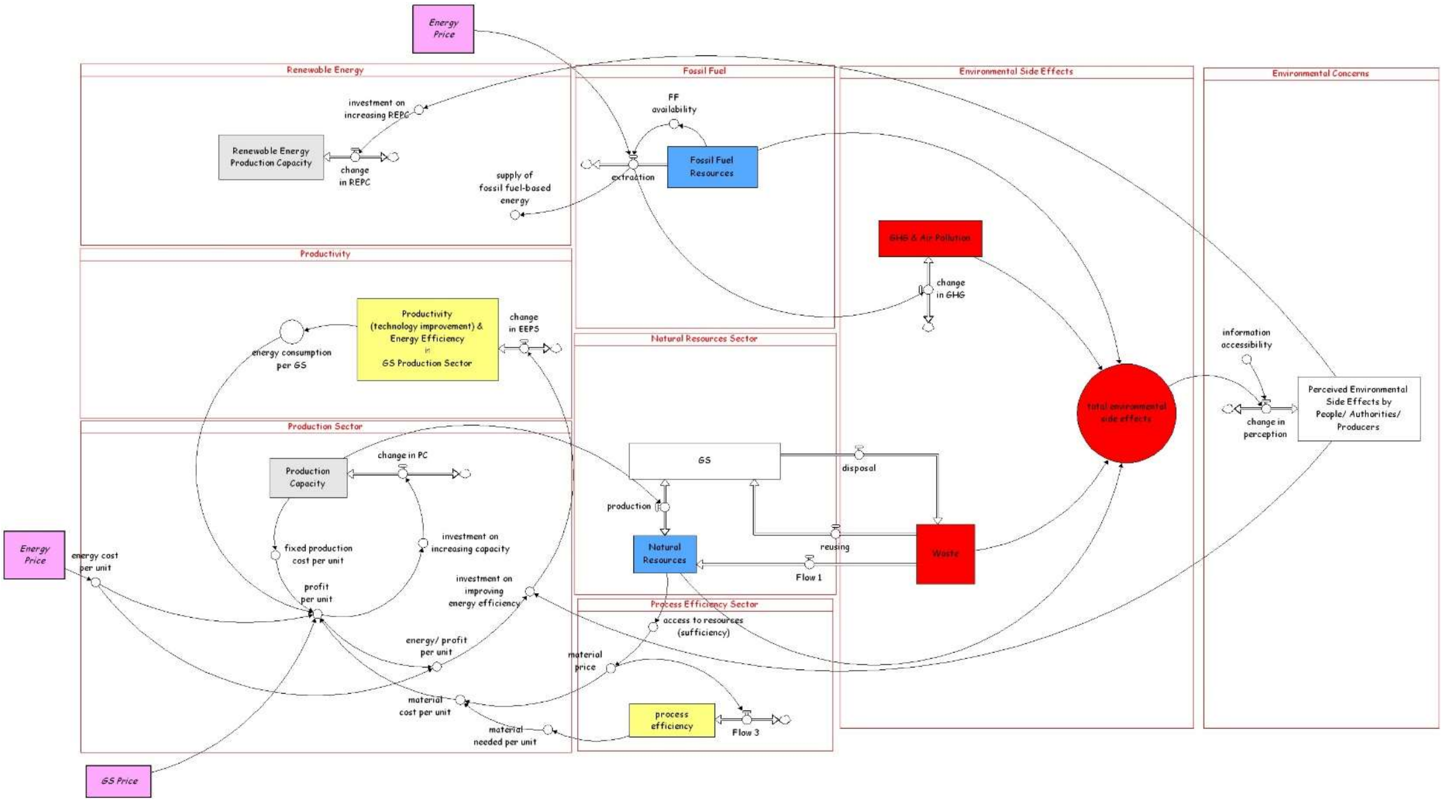

Figure 2: Part 2 of the model

Production capacity can increase under the influence of two positive loops (Figure 3):

R-production capacity: production capacity↑ ⇨ income & profit↑ ⇨ investment on increasing production capacity↑ ⇨ production capacity

R-economies of scale: production↑ ⇨ fixed cost per product unit↓ ⇨ profit↑ ⇨ investment on increasing production capacity↑ ⇨ production capacity

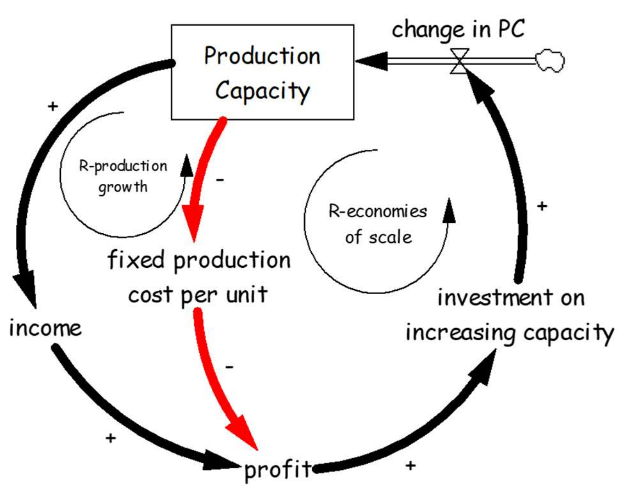

Figure 3: A generic model for market growth (two positive loops increasing production capacity)

However, no growth can continue forever. There are four balancing loops (Figure 4) which control the reinforcing loops (so it is a "limits to growth" or "attractiveness principle"[2] archetype).

B1-demand limitation: one of the limiting factors for production growth is the limitation of demand. To include this mechanism, we used ***the generic "invisible hand" model***. According to this, the development of production will reduce the price and thus profitability. This mechanism is the "limits to growth" archetype

B2-energy price: another factor limiting production growth is the price of energy. With the increase in production, the demand for energy and thus the energy price increase. The rise in energy prices also reduces profitability and the incentive to invest and increase production. To show this effect, we have again used the generic model of the "invisible hand."

B3-resource limitation: another factor is resource limitations. We have used the "material flow" generic structure to show the flow of resources. Resources are used & converted into products; then products are discarded after some time and stored in "waste" stock. Waste may be decomposed, reused, or recycled. Reducing resources increases raw materials' price and thus decreases profitability.

B4-environmental side effects: the fourth and last factor limiting growth is environmental factors. Increasing production and energy consumption can cause various environmental problems, such as depletion of resources, air pollution, and waste production. With the increase of environmental issues, taxes will be approved that take into account externalities on the price of energy and products.

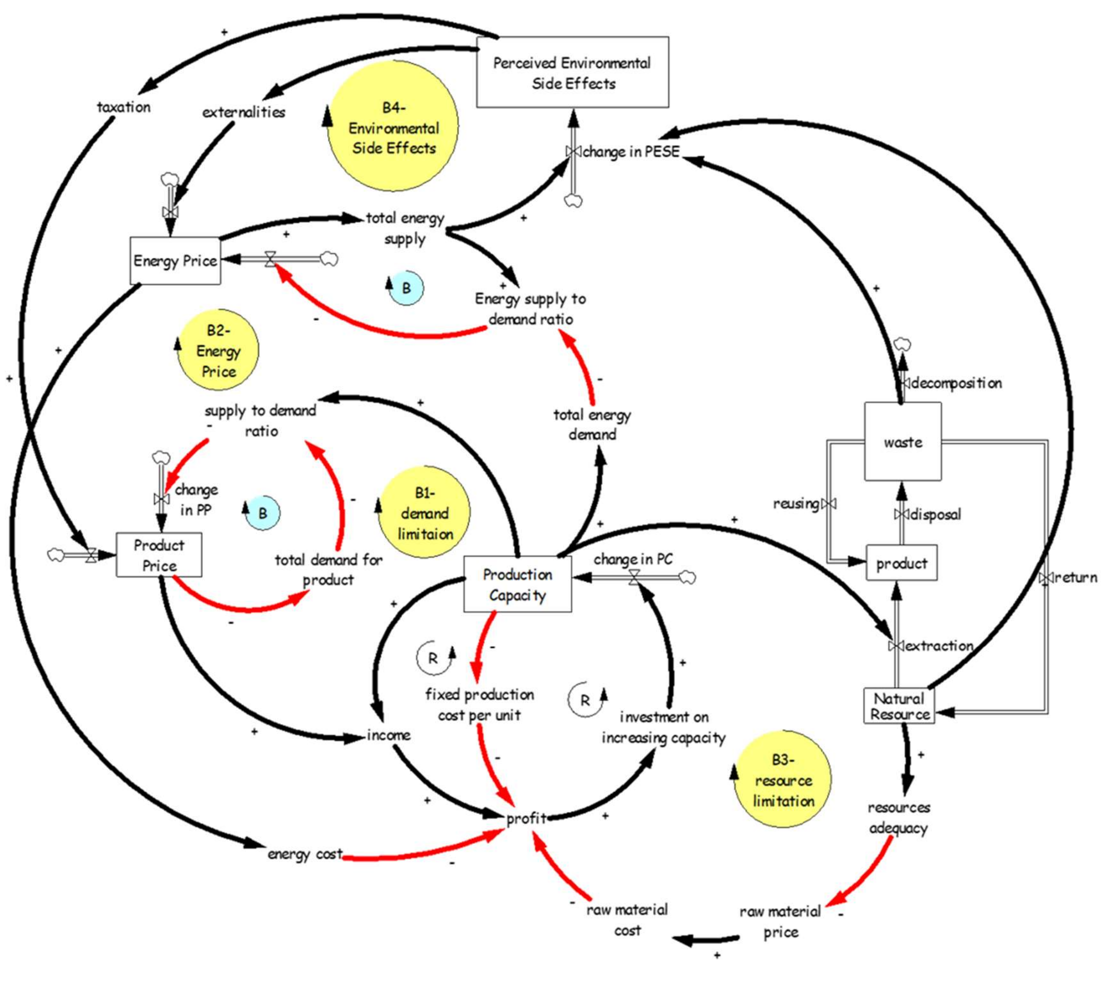

Figure 4: Four balancing loops which control production capacity

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[2] When the number of growth limits is more than one, you can use the "attractiveness principle" expression instead of the "limitation to growth" archetype.

We mentioned four balancing loops controlling production growth. Any solution and action that weakens these controlling factors and negative loops (e.g., if we use the circular economy, find or use a method that reduces environmental effects (such as Solidification and Storage of Carbon Dioxide), or improve energy efficiency) are practically "fixes that fail".

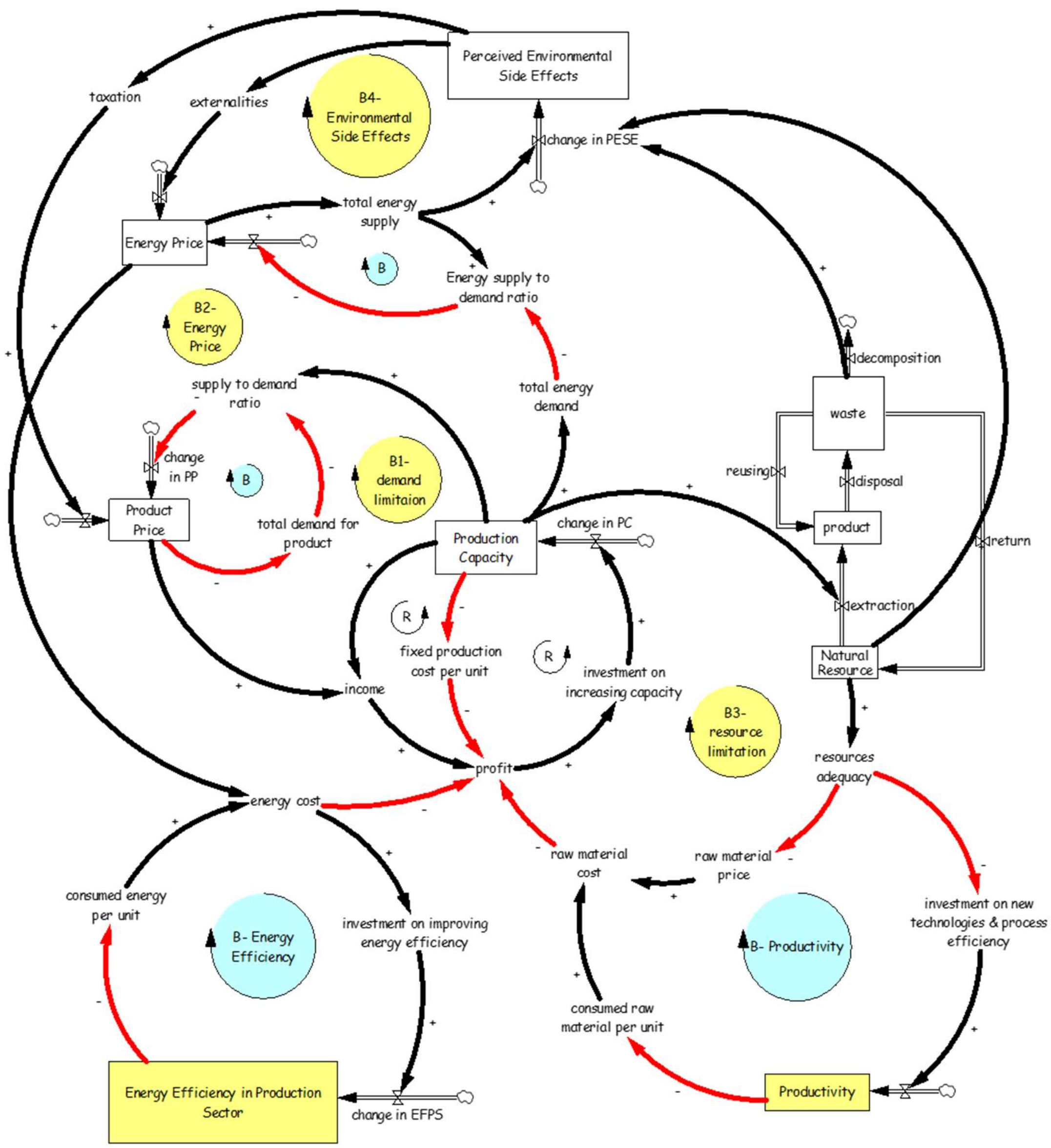

Figure 5

To illustrate "output" RE, we will focus on "resources consumption" in the following. As seen in this Figure 5, as resource adequacy decreases, investment in developing and using technologies and process efficiency increases, creating a negative loop that weakens B3 (resource limitation). It apparently can decrease resource consumption, but at the same time strengthen the other positive loop which cause more resource consumption (fixes that fail archetype, Figure 6).

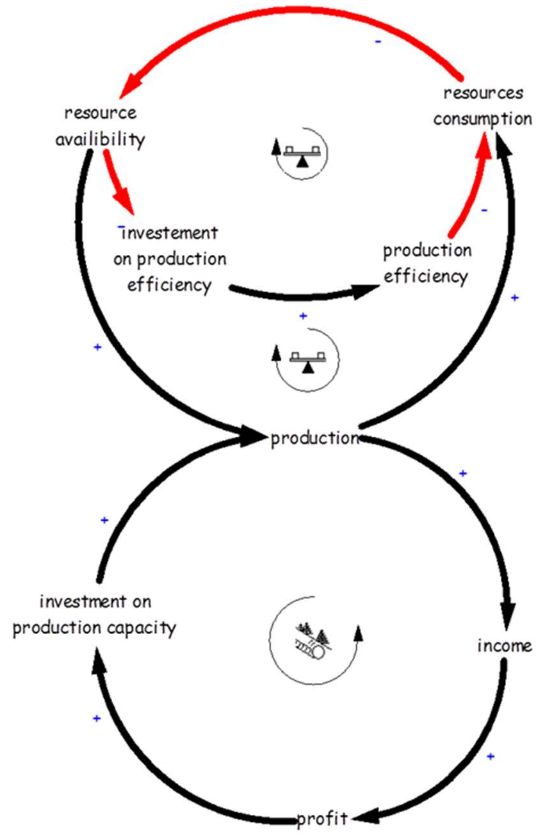

Figure 6: Simple schematic illustration of the "fixes that fail" archetype for "output" RE mechanism

The other archetype that we can see in Figure 5, is the "shifting the burden" archetype for "re-spending" indirect RE mechanism (Figure 7). Due to the use of fossil fuels, the world is facing many environmental problems such as global warming. There are two solutions for it. A temporary/ symptomatic solution (i.e., improving energy efficiency in the household sector) and a fundamental solution (i.e., replacing fossil fuels with renewable energy) which can uproot the problem but require much more time and effort. The symptomatic solution, however, is much more attractive usually since it has less difficulty and affects much sooner. Nevertheless, improving energy efficiency in household sector, through three mechanisms can increase the energy consumption in production sector, neutralizing some environmental gains of reducing energy consumption in household sector. First, by reducing energy demand in the household sector, energy prices decrease, which increases profitability and reduces the incentive to improve energy efficiency in the industrial sector. Second, by reducing energy consumption in the home sector, people can buy more goods and services than before with the saved money. This increase in demand causes an increase in product price, profit, and as a result, an increase in production. As can be seen, these 3 positive loops reduce the effect of improving productivity on reducing environmental problems.

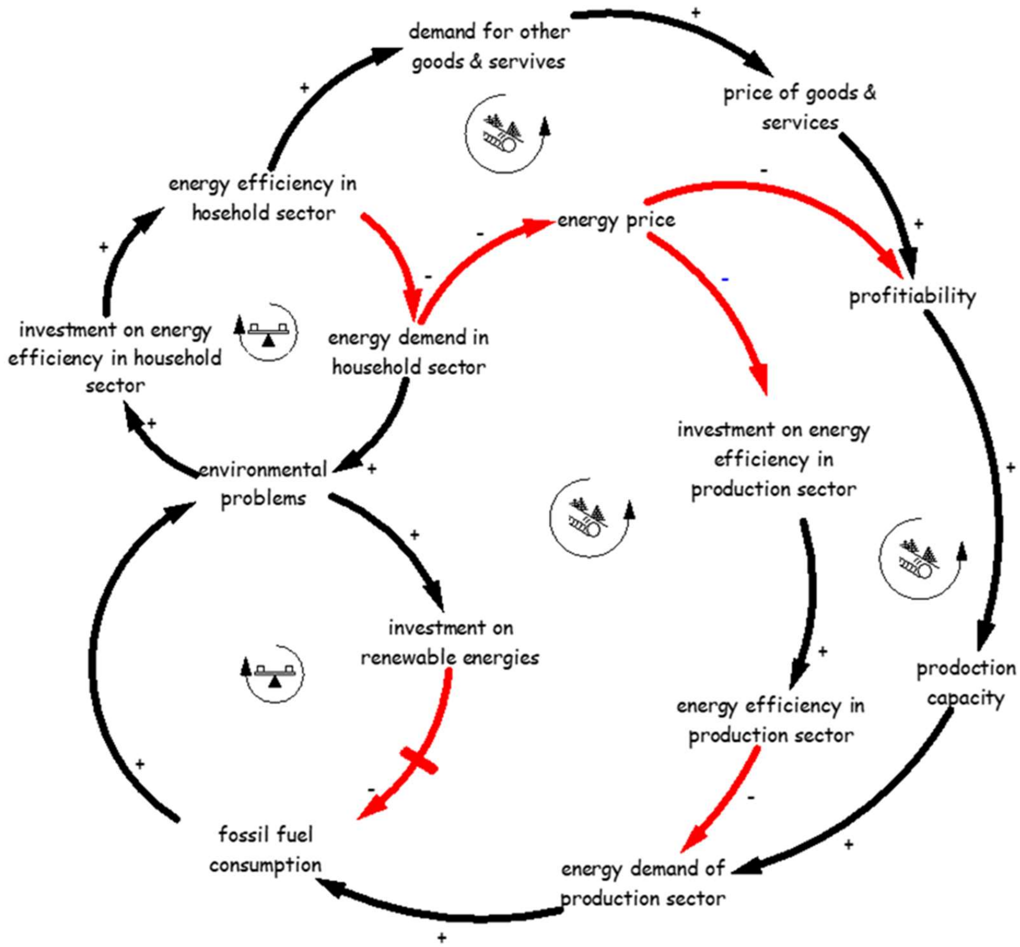

Figure 7: Simple schematic illustration of the "shifting the burden" archetype for "re-spending" RE mechanism

Summary

Understanding and managing rebound effects is vital to ensure that energy efficiency and conservation measures are effective and achieve their intended goals, both in terms of environmental sustainability and economic efficiency. Rebound effects can undermine policy goals and make it more difficult to achieve environmental or energy policy objectives. For example, if policies promoting energy efficiency or conservation measures are not designed to account for rebound effects, they may fail to achieve their intended goals. Rebound effects can lead to an increase in resource consumption and greenhouse gas emissions, thereby offsetting the gains from energy efficiency or conservation measures. For example, if people switch to more fuel-efficient cars but drive more frequently or longer distances, the net result may be increased energy consumption and emissions. Rebound effects can also have unintended economic consequences, such as reducing the cost savings or economic benefits of energy efficiency measures. If people save money on their energy bills by using more efficient appliances, they may spend the savings on other energy-consuming goods or services, reducing the net economic benefit. Moreover, rebound effects can have social consequences, such as reducing the health benefits of energy efficiency measures. For example, if people use energy-efficient lighting to save money, but then leave the lights on longer or use more lighting in general, this can lead to increased light pollution, which can have negative health impacts.

Earlier research on rebound effects was primarily focused on economic theories, which attributed the cause of RE to factors such as prices, income, and price elasticity. More recently, alternative theories from energy economics, ecological economics, socio-psychological, and socio-technological perspectives have emerged. However, these theories tend to view the issue from a narrow perspective, and a holistic view is necessary to find a sustainable solution. System dynamics (SD) is a useful tool in this context, as it can provide a more comprehensive perspective by integrating different viewpoints. A review of the literature on SD-RE reveals a gap in research that examines the relationship between different sectors and that incorporates various theories and perspectives on RE. This study is the first attempt to examine the rebound effect by utilizing system archetypes, which has not been attempted before. However, further research is required to build upon the proposed model.

As the last remark, when employing system archetypes to conceptualize a problem, there is a significant risk that choosing an archetype will mark both the beginning and end of the analysis [40]. Novice modelers in particular may select an inappropriate archetypal structure as a modeling basis or have a preconceived view of the problem because of using these structures [41]. In practice, it is often beneficial to use the archetypes in parallel throughout the process to guide high-level thinking whilst detailed modelling is taking place [42]. In fact, it is a two-way street; we need to simultaneously work on the existing archetype on the one hand, and on the other hand, build a detailed model without thinking about the archetypes, and finally merge them. There are some computer-aided methods (e.g. Schoenenberger et al. [41]) which can help us to find archetypes in a given model.

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