Time-saving innovations and their impact on energy use: some lessons from a household-production-function approach

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Abstract: This paper highlights a specific aspect of time allocation within households: the impact of time-saving technological progress on time use as well as on energy use for non-productive activities. It shows that, under standard assumptions, time-saving technological progress causes a feedback on time use (a rebound effect). If the feedback is strong, households may not 'save' any time at all although they constantly invest in time-saving devices. Moreover, innovations of a time-saving nature tend to have a substantial impact on energy consumption. When the opportunity costs of time (the wage rate) are high and energy prices are low, time-saving innovations are also likely to increase energy consumption.

JEL Classification: D13; Q41.

Keywords: household production; allocation of time; time-saving innovations; rebound effect; energy use.

Reference to this paper should be made as follows: Binswanger, M. (2004) 'Time-saving innovations and their impact on energy use: some lessons from a household-production-function approach', *Int. J. Energy Technology and Policy*, Vol. 2, No. 3, pp.209–218.

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1 Introduction

Time may be viewed as a fundamentally scarce resource in the economy. Households' decisions with regard to time, are of particular relevance because they "ultimately determine the relative prices of goods and services, the growth pace of real output, and the distribution of income" (Juster and Stafford, 1991, p.471). In this paper, we will highlight one specific aspect of time allocation within households: the impact of time-saving technological change on time use as well as on energy use for non-productive activities. As already emphasised by Becker (1965), technological progress has enabled a large increase in the efficiency[1] of the use of time spent on leisure activities and consumption. An increase in the efficiency of consumption due to some time-saving innovations implies a decline in the time input required to produce a unit of a service. The decline reduces the costs associated with time, which is conventionally measured by forgone earnings. The effect is stronger, the higher the earnings are, and, therefore, the higher the forgone income from work. The secular increase in wages since World War II in all developed countries has created a strong incentive to implement time-saving devices as the opportunity costs of time are constantly rising.

The examples of increasing time efficiency that are mentioned by Becker (1965) are supermarkets (saves shopping time), automobiles (saves time spent on transport), sleeping pills (saves 'unproductive' time spent in bed lying awake), electric razors (saves time spent on shaving, which hitherto had lasted longer because men used to go to the barber's shop for this purpose), and telephones (saves time spent on visiting people's home). More recently, new developments in information technology, e.g. the internet, may also be interpreted as time-saving innovations, as they reduce the necessary time inputs for the production of many services. For example, e-commerce further increases the time efficiency of shopping, the use of e-mails reduces the time spent on writing and sending letters, and access to the internet reduces the time needed to gather information on many subjects.

But do time-saving innovations really 'save' time? The answer to this question is not trivial, because time-saving innovations also lower the 'time cost' of producing a particular service measured by the forgone income from work (opportunity costs). Consequently, if a service can be produced in less time due to an increase in time efficiency, households will have an incentive to demand more of this service and substitute it for other services that are more time intensive in order to minimise the forgone income from work. For example, a time-saving innovation such as a faster mode of transport may cause people to commute longer distances because mobility becomes more time efficient, but induces them to eat in fast food restaurants instead of cooking at home as they substitute the now less time intensive service (commuting) for the more time intensive (cooking at home). An increase in time efficiency frequently leads to a feedback on time use, which we will call a 'rebound effect with respect to time'. Sometimes, it results in the paradoxical effect that households will not 'save' time spent on a particular activity although they invest a lot in time saving appliances. This phenomenon has already been described by Linder (1970) and referred to as 'time famine' in Sullivan and Gershuny (2001).

The rebound effect is well known with respect to energy, another important input to household production. Since the 1980s, the question of how energy efficiency improvements affect the energy consumption of households has been a major issue among energy economists – see Binswanger (2001), Brookes (2000) or Greening et al. (2000) for surveys of the relevant literature. In particular, Khazzoom (1980, 1986) and Wirl (1997) came up with a precise definition of the rebound effect with respect to energy, whose existence was also supported by empirical research. The definition of the rebound effect is based on the following considerations: if technological progress makes equipment more efficient with respect to a certain production input, less of that input is needed to produce the same amount of product or service – ceteris paribus. However, the amount of product or service usually does not stay the same. Because the equipment becomes more efficient, the cost per unit of product or service that is produced with this equipment falls, which, in turn, increases the demand for the product or the service. Consequently, part of the input-saving potential initiated by technological progress is 'lost' because of increased demand for the product or service associated with the input use.

This paper presents the rebound effect, not with respect to energy, but with respect to time in a simple framework that is built on the original household-production-function model developed by Becker (1965) and Michael and Becker (1973). But the model also stresses the importance of energy as a further input of production. This is of special interest because technological change of a time-saving nature can have a large influence on energy use, as an increase in time efficiency (for example, faster modes of transport) is frequently associated with an increase in energy consumption. The effect will be especially strong when wages are high and, at the same time, energy prices are low, as is currently the case in most industrialised countries. High wages, which represent the opportunity costs of time, in combination with low energy prices, encourage the use of time-saving but energy-intensive devices, leading to an overall increase in energy use as people constantly try to 'save' time. Therefore, according to our model, time-saving innovations cause a feedback on the use of time as well as energy.

The following section shows the direct impact of time-saving innovations on the demand for services. Section 3 highlights the potential effects of time-saving innovations on energy use and shows that the effect crucially depends on the relative prices of energy and time. Section 4 concludes.

2 Direct impact of time-saving innovations

Ever since Becker's seminal paper, 'A Theory of the Allocation of Time', which was published in 1965, the household-production-function approach has become one of the major tools for analysing the allocation of time to various activities within households – see Juster and Stafford (1991) or Gronau (1997) for more recent surveys on the relevant literature. According to this framework, households derive utility from consuming services rather than from market goods itself. These services, such as mobility (measured in passenger kilometres) or comfortable room temperature, are supposed to be the output of a household-production-function f_i:

$$s_i = f_i\,(t_i, e_i, \mathbf{x_i}). \tag{1}$$

f_i describes how households 'produce' an amount s_i of service i by using time, t_i , energy, e_i, and market goods, including capital goods, which are denoted by the vector $\mathbf{x}_i$. For simplification, further inputs such as education are ignored in production function (1). Furthermore, it is assumed that any household's utility depends solely on the amounts s_1, ... ,s_n of services produced within the household, respectively:

$$U = u(s_1, s_2, ..., s_n) \quad \text{with} \quad \frac{\partial u}{\partial s_i} > 0 \quad \text{and} \quad \frac{\partial^2 u}{\partial s_i^{\,2}} < 0 \quad \text{for } i = 1, ..., n. \tag{2}$$

The available time budget T for a household is split up into the hours t_W spent on the job and the overall time necessary to produce all the household services:

$$T = t_W + \sum_{i=1}^{n} t_i \tag{3}$$

Note specifically that t_W does not enter the utility function (2). Finally, households face a budget constraint, which reads

$$t_W\, w = \sum_{i=1}^{n} (p_e e_i + \mathbf{p}_i \mathbf{x}_i), \tag{4}$$

if the household's non-wage income is zero. The notation for the price for energy is p_e, and the vector $\mathbf{p}_i$ captures the prices of the market-good inputs required for the service i. The time constraint (3) and the budget constraint (4) can be combined in a single resource constraint on the household's 'full income' S, a concept introduced by Becker (1965):

$$\mathrm{S} := wT = \sum_{i=1}^{n} (wt_i + p_e e_i + \mathbf{p}_i \mathbf{x}_i). \tag{5}$$

The 'full income' S is the maximum money income that a household could achieve if all available time were to be spent working at the wage rate w. On the basis of (5), the Lagrangian L for the utility maximisation problem subject to both budget constraints (3) and (4), can be expressed as

$$L := u(s_1, s_2, ..., s_n) - \lambda \left[\sum_{i=1}^{n} (wt_i + p_e e_i + \mathbf{p}_i \mathbf{x}_i) - S \right]. \tag{6}$$

If, additionally, joint production – especially joint usage of time – is ruled out, the first-order conditions with respect to service j, read according to Michael and Becker (1973):

$$\frac{\partial u}{\partial s_j} = \lambda \left[w \frac{\partial t_j}{\partial s_j} + p_e \frac{\partial e_j}{\partial s_j} + \mathbf{p}_j \frac{\partial \mathbf{x}_j}{\partial s_j} \right]. \tag{7}$$

If, for example, there is a time-saving innovation concerning the production of service j, this will result in a decline in $w \partial t_j / \partial s_j$, since less time is needed to produce an additional unit of this service. The time-saving impact will be stronger the higher the wage rate w is. As a consequence, because of $\partial^2 u / \partial s_i^2 < 0$, the demanded amount s_j for service j increases. In other words, due to the time-saving innovation, households will demand more of this service as it becomes cheaper in terms of forgone income from work.

There is quite a lot of evidence suggesting that time-saving innovations in transport lead to an increase in the demand for mobility as predicted by our analysis: If j stands for mobility, for example, and there is a time-saving innovation in transportation technology, such as faster cars or better roads, people will travel longer distances, since a certain distance can be travelled at a lower opportunity cost. One early hypothesis in this context is that of a fixed travel-time budget, which states that the travel-time budget of households is relatively stable – see Goodwin (1978), Sharp (1981, p.99), Zahavi et al. (1981) and Schaffer (2000).

In other words, whenever there is a time-saving innovation that allows people to travel the same distance within less time, according to the fixed travel-time-budget hypothesis, they will increase their mobility at an amount that exactly compensates for the time saved due to the innovation. This hypothesis, however, is not commonly accepted. There is also some evidence that the total time allocation to mobility may even have increased in the past in spite of many time-saving innovations – see Schipper (1997). Moreover, there are large differences between countries: the average distance travelled in the USA, for instance, is much higher than in Europe or Japan.

The rebound effect with respect to time, though, is also of potential relevance to more recent innovations regarding information technology. The use of e-mails, which is more time-efficient than sending letters, induces people to send more messages than they ever would have if they only had the post-office option. Therefore, part of the time-saving potential of the innovation 'e-mail' is lost because of the rebound effect. The same can also be said for the internet. For example, the internet substantially has increased the time-efficiency of finding information on a specific subject. But it also induces people to 'surf' a lot on the net, which, again, may be interpreted as a rebound effect with respect to time.

3 Impact of time-saving innovations on energy use

In the multi-services model presented in the previous section, income and substitution effects play a major role. An important effect of a time-saving innovation in the production of a service *i* is the substitution of this service for more time-intensive services. This is because the opportunity costs of producing the service *i* shrink due to time-saving innovations. Moreover, besides the substitution of one service for another, there might be a substitution effect among the inputs energy and time in the production of a service: Time-saving innovations are likely to cause an increase in energy demand, because time saving is frequently accompanied by an increase in energy intensity. Faster modes of transport, for instance, require less time for driving a certain distance, but they usually need more energy than slower modes of transport. (However, as long as p_e is much smaller than w, as is typical in developed countries, the effect of the increase in energy intensity on the demand for a service will be weaker than the effect of the decrease in time intensity.)

In order to analyse the substitution effect between two services, say *j* and *k*, as a consequence of a time-saving innovation for service *j*, we need the ratio of the marginal utilities of these two services – see the respective first-order condition (7) for service *j*, which has to equal the ratio of their marginal costs π_j and π_k:

$$\frac{\frac{\partial u}{\partial s_j}}{\frac{\partial u}{\partial s_k}} = \frac{w\frac{\partial t_j}{\partial s_j} + p_e\frac{\partial e_j}{\partial s_j} + \mathbf{p}_j\frac{\partial \mathbf{x}_j}{\partial s_j}}{w\frac{\partial t_k}{\partial s_k} + p_e\frac{\partial e_k}{\partial s_k} + \mathbf{p}_k\frac{\partial \mathbf{x}_k}{\partial s_k}} = \frac{\pi_j}{\pi_k}. \tag{8}$$

For the analysis of substitution effects among the production factors time and energy, specifically, we differentiate the Lagrangian L in (6) with respect to t_j and e_j in order to get their optimal quantities in 'producing' s_j. For the least-cost input combination of t_j and e_j, we then obtain the following condition that implies that the ratio of marginal utilities induced by each factor must equal their factor price ratio:

$$\frac{\frac{\partial u}{\partial t_j}}{\frac{\partial u}{\partial e_j}} = \frac{\lambda \cdot w}{\lambda \cdot p_e} \quad \Leftrightarrow \quad \frac{\frac{\partial u}{\partial s_j} \cdot \frac{\partial s_j}{\partial t_j}}{\frac{\partial u}{\partial s_j} \cdot \frac{\partial s_j}{\partial e_j}} = \frac{w}{p_e} \quad \Leftrightarrow \quad \frac{\frac{\partial s_j}{\partial t_j}}{\frac{\partial s_j}{\partial e_j}} = \frac{w}{p_e} \tag{9}$$

Substitution effects among inputs can be important if there is a change in the ratio of the factor prices. If, for example, wages increase in relation to energy prices, this will induce a substitution of energy for time in the production of all services that require time as well as energy as inputs for production. Faster but more energy-intensive modes of transport will be used in order to 'produce' a certain quantity (e.g. 100 km) of the service 'mobility'[2].

Both substitution effects can only be analysed in further detail if we are ready to specify the production function (1). In what follows, we will assume that the amount s_j of service j is the result of a Cobb-Douglas production function that belongs to the family of linear-homogeneous functions, where a household's technology exhibits constant returns to scale and where marginal costs equal average costs[3]. As shown by Pollack and Wachter (1975), the household-production-function approach rests on the assumption of linear homogenous production functions once they allow for substitutability among inputs. It makes the implicit 'service prices' π_j and π_k in (8) independent of a household's preferences, which is important because, otherwise, demand functions based on 'service prices' are seriously misleading.

With respect to service j, for example, the Cobb-Douglas production technology may be specified as:

$$s_j = (\rho_j t_j)^{\alpha_j} e_j^{\beta_j} x_j^{1-\alpha_j-\beta_j} \tag{10}$$

The impact of time-augmenting technological change is captured by the coefficient ρ_j, which is an index of the efficiency of time in the production of s_j[4]. Basically, transport technologies, just like energy technologies, are embodied in physical capital; higher efficiency, therefore, usually comes at a cost. However, in order to keep the model simple, we assume that time-saving innovations are free and that an increase in time-efficiency is exogenous to households[5].

Principally, using a production function where substitution among inputs is possible, requires a two-step optimisation process. First, households must choose the least-cost combination of inputs for the production of the services from which they derive utility. And, second, they must choose the optimal combination of the optimally produced services in order to maximise their utility.

Upon differentiating s_j from (10) with respect to t_j and e_j, and inserting the results,

$$\frac{\partial s_j}{\partial t_j} = \frac{\alpha_j \cdot s_j}{t_j} \quad \text{and} \quad \frac{\partial s_j}{\partial e_j} = \frac{\beta_j \cdot s_j}{e_j}, \tag{11}$$

into (9), we get the necessary conditions for the least-cost input combination for the production of service *j* in the amount of s_j:

$$\frac{\alpha_j \cdot e_j}{\beta_j \cdot t_j} = \frac{w}{p_e} \quad \Leftrightarrow \quad e_j = \frac{w}{p_e} \cdot \frac{\beta_j}{\alpha_j} \cdot t_j \tag{12}$$

As can be seen from (12), the least-cost input combination is not affected by a change in ρ_j, and time-augmenting innovations do not have any influence on the optimal ratios among inputs. Similarly, we get

$$\frac{\alpha_j \cdot x_j}{(1-\alpha_j - \beta_j)t_j} = \frac{w}{p_j} \quad \Leftrightarrow \quad x_j = \frac{w}{p_j} \cdot \frac{(1-\alpha_j - \beta_j)}{\alpha_j} \cdot t_j \tag{13}$$

Next, we will show how, under the assumption of Cobb-Douglas production function (10), time-augmenting technological change affects the demand for the two services s_j and s_k. We differentiate the Lagrangian *L* in (6) with respect to t_j and t_k in order to get the following first-order condition:

$$\frac{\frac{\partial u}{\partial t_j}}{\frac{\partial u}{\partial t_j}} = \frac{\lambda \cdot w}{\lambda \cdot w} \quad \Leftrightarrow \quad \frac{\frac{\partial u}{\partial s_j} \cdot \frac{\partial s_j}{\partial t_j}}{\frac{\partial u}{\partial s_k} \cdot \frac{\partial s_k}{\partial t_k}} = 1 \quad \Leftrightarrow \quad \frac{\frac{\partial u}{\partial s_j}}{\frac{\partial u}{\partial s_k}} = \frac{\frac{\partial s_k}{\partial t_k}}{\frac{\partial s_j}{\partial t_j}} = \frac{\alpha_k s_k t_j}{\alpha_j s_j t_k} \tag{14}$$

In the equation on the right, the derivatives given in (11) are already inserted. Substituting the Cobb-Douglas production technology (10) for s_j and s_k, inserting (12) and (13), and rearranging finally yields:

$$\frac{\frac{\partial u}{\partial s_j}}{\frac{\partial u}{\partial s_k}} = \frac{\left(\rho_k \frac{\alpha_k}{w}\right)^{\alpha_k} \left(\frac{\beta_k}{p_e}\right)^{\beta_k} \left(\frac{1-\alpha_k - \beta_k}{p_k}\right)^{1-\alpha_k-\beta_k}}{\left(\rho_j \frac{\alpha_j}{w}\right)^{\alpha_j} \left(\frac{\beta_j}{p_e}\right)^{\beta_j} \left(\frac{1-\alpha_j - \beta_j}{p_j}\right)^{1-\alpha_j-\beta_j}}, \tag{15}$$

where the ratio of the marginal utilities of the services *j* and *k* only depends on exogenous parameters. From (15) we can see the impact of a time-augmenting innovation. *Ceteris paribus* an increase in ρ_j will induce a substitution of *j* for *k*, leading to an increase in the demand for *j*. The effect will be stronger the larger the coefficient α_j is, and, at the same time, energy consumption will also increase as long as $\beta_j < \beta_k$.

Again, mobility may serve as the main example to illustrate the conclusions derived from this section. Time-saving innovations leading to faster modes of transport will cause an increase in mobility because of the decline in the opportunity cost associated with mobility (recall Section 2). But time-saving innovations also induce the substitution of mobility, which becomes more time-efficient, for other time-intensive services such as cooking at home or gardening. Furthermore, faster modes of transport are usually also more energy intensive than slower modes of transport. This feedback on energy use is very common and not restricted to mobility. Washing machines, vacuum cleaners and lawn mowers are all predominantly time-saving innovations that increase the energy intensity of services, such as washing, cleaning and gardening.

However, we must stress the fact that things may be reversed with respect to time-saving innovations regarding information technology, where time-saving innovations may induce substitution of less energy-intensive services for more energy-intensive services. If, for example, e-commerce is used as a substitute for traditional shopping done by car, or if surfing the internet substitutes for driving around, the result will be a decrease in the overall use of energy. Therefore, information technologies may possess the rare feature of being time saving and energy saving at the same time.

Finally, emphasising the role of time-saving innovations provides another strong argument in favour of taxing energy e.g. as part of an ecological tax reform. As can be seen from (9), the substitution towards less time-intensive but more energy-intensive services caused by a time-saving innovation will be more pronounced the higher the average wage rate w is and the lower the energy price p_e. Consequently, the development of the relative prices of labour and energy in developed countries over the last few decades that led to an increase in wages relative to energy prices strongly supported the induced substitution effects, since it paid off to save time, but it did not pay off to save energy[6].

4 Conclusion

This paper has analysed how time-saving technological progress in households affects the use of time as well as energy by using a household-production-function approach as developed by Becker (1965) and Michael and Becker (1973). This approach is well suited for uncovering the economic logic behind the rebound effect, the feedback on time use caused by time-saving innovations. The rebound effect describes the fact that part or all of the time-saving potential initiated by time-saving technological progress is 'lost' because of increased demand for a service associated with that time use. The reason for this feedback on time use is the decline in the cost per unit of the service that is caused by the increase in time efficiency, which in turn increases the demand for the service. If the rebound effect is high because the price elasticity of the service demand is high, the increase in time efficiency can even increase the demand for time, which is the time-saving paradox where people's attempts to save time spent on the production of a particular service actually increase the time spent on the production of this service.

The discussion of the rebound effect originates from energy economics, where the question of how much energy can really be saved by energy-saving technology is a much debated issue. Empirical research suggests that the rebound effect with respect to energy is rather small during times of low energy prices – see, for example, Greening et al. (2000); Haas and Schipper (1998). This paper, however, suggests that the rebound effect with respect to time may actually be of much greater relevance than the rebound effect with respect to energy during periods when wages, which represent the opportunity costs of time, are relatively high compared to energy prices. Under these circumstances, it frequently pays off to save only time but not energy, because energy costs represent a negligible portion of a household's budget. Consequently, a fall in the time cost of a service may also cause a substantial increase in the demand for the service that causes the rebound effect with respect to time. Although the rebound effect with respect to energy may be of negligible size, energy use is sometimes strongly affected by the rebound effect with respect to time.

Time-saving devices usually require more energy, as is most evident from transport where higher time efficiency (faster modes of transport) tends to be associated with a larger input of energy. If there is a time-saving innovation that affects the production of a particular service such as mobility, it can be produced in less time, and households will demand more of this service (the rebound effect with respect to time) and substitute it for other services that are more time intensive but usually less energy intensive. In this case, time-saving technological progress will also lead to an increase in energy use. This mechanism is of special importance to environmental policy and strategies of sustainable development, since it provides an alternative argument for taxing energy in order to lower the impact of the rebound effect with respect to time on energy use, which is most relevant in relation to transport services.

The analysis presented in this paper is still based on highly stylised and static models that are far from giving an exact description of reality. Their main purpose is to highlight some aspects of time-saving innovations that are often neglected. Therefore, the models also ignore several problems inherent to the analysis of time-allocation decisions of households, such as the joint use of time for several services (see Pollack and Wachter 1975), the fact that people derive utility from certain uses of time (such as parental child care or watching TV) while time spent on working in the market may involve disutility, and the problem of actually valuing non-market time (see Juster and Stafford, 1991, pp.505–507). But these simplifications should not affect the main thrust of the paper. Further empirical research is needed, however, in order to estimate the actual size of the rebound effect with respect to time in relation to different modes of time-saving innovations. And there is also a need for studies on the exact relation between the introduction of specific time-saving devices and their impact on energy use.

Acknowledgement

I am grateful for the valuable comments and suggestions of an anonymous referee and, in particular, of the editor, Manuel Frondel.

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Notes

[1]Becker (1965) uses the expression 'time productivity' instead of 'time efficiency', meaning the same thing.

[2]See Gronau (1970) on how the choice of the mode of transportation is affected by the price of time.

[3]Michael (1973) also uses the assumption of a linear homogeneous production function in order to investigate the effect of education (an increase in home efficiency with respect to schooling) on the demand for time and other inputs.

[4]Saunders (1992, 2000) makes the same assumption for energy (fuel) efficiency gains, which are modelled as energy- (fuel-) augmenting technological change.

[5]This assumption may be justified on the grounds that the introduction of many time saving innovations, such as faster modes of public transport, cannot directly be influenced by households, and that they react by adapting their behaviour to the new situation.

[6]In transport, this trend was also supported by the widening gap between land prices in cities and land prices on the country side, which made people move out of the cities.