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## "Essays on Renewable Energy, Growth and Sustainable Development"

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## Structure of the dissertation

**Introduction**

**Paper I**: *"Can renewable energy grant sustainable development in an oil fed economy?"*

**Paper II:** *"Simulating exogenous and endogenous technology when depletables, renewables and pollution co-exist: how to achieve sustainability?"*

**Paper III:** *"Bioenergy and foodsecurity: Who benefits and who loses? The importance of the ceteris paribus assumption"*

## Introduction

If governments today around the world stick with current policies... the world's energy needs would be over 50 percent higher in 2030 than today...the challenge for all countries is to put in motion a transition to a more secure, lower carbon energy system, without undermining economic and social development...vigorous, immediate and collective policy action by *all* governments is essential to move the world onto a more sustainable energy path..." (IEA 2007, pg 41, selected lines).

The current energy portfolio which heavily relies on fossil fuels is not sustainable and the energy decisions of today will be essential in trying to curb climate change impacts. The need for energy diversification is a must and renewable non-polluting resources need to contribute much more to energy generation. In fact, the non-sustainability of fossil fuel economies no longer lies with the limited availability of those resources but with the greenhouse gas emission levels the current energy pattern leads to. **This thesis investigates the relationship between the availability of renewable resources and sustainability.** The thesis is divided in three papers examining some critical questions regarding renewable energy use. The first two papers take a long term perspective and investigate: How can we achieve strong and weak sustainability? What contribution does technology make? What role does substitutability between renewable and depletable resources play? How do production and consumption assumptions affect the results? The third paper takes a different viewpoint and looks at bioenergy and household level welfare impacts.

Current energy demand is mainly met by fossil fuels and consequent $CO_2$ concentration levels are too high; further, there is a wide divide in energy demand across regions. Fossil fuels meet 80.9 percent of energy demand today and are estimated to absorb the majority of projected demand. World primary energy demand is projected to more than double between 2005 and 2030 (see Table 1 and 2)[1]. Developing economies will be the largest contributors to this projected growth because of fast economic and population growth rates. Fossil fuels are projected to

[1] The IEA Energy Outlook presents a number of scenarios that make different policy and growth assumptions. Here we refer to their baseline scenario, the reference scenario.

meet 84 percent of the total energy demand increase. Coal is predicted to absorb a large share of the increase in demand, reaching a share of 28.2 percent in 2030 (IEA, 2007). At present, the gap existing between primary energy use per capita across regions in the World is high. OECD industrialised countries consume approximately 4.68 toe/capita[2] compared to 1.62 toe/capita in the Middle East and North Africa, 0.72 toe/capita in Asia including China and 0.6 toe/capita in Sub-Saharan Africa. Thus one sixth of today's world population consumes approximately 50% of the total primary energy supply. The global population is growing by approximately 80 million people a year and has doubled since 1960, estimated to reach 8.2 billion by 2030. Thus, pressures on the energy demand system will be increasing as countries progress, population grows and the gap in energy per capita levels narrow (WEA 2002, WEA 2004, UN 2005).

Energy related pressures on the environment have been heavily debated but, finally, the fourth IPCC assessment acknowledges that climate change impacts could be severe if action is not taken immediately. In 2005 the global atmospheric concentration of $CO_2$ was estimated at 379 parts per million (ppm), rising from pre-industrial level of 280 ppm. Rising energy demand under the IEA reference scenario predictions, suggest that energy-related $CO_2$ emissions will increase by 57 percent over the 2005-2030 reference period. The fourth assessment of the IPCC reports that $CO_2$ concentrations need to peak and decline thereafter in order to ensure that $CO_2$ concentration stabilises. If a safe $CO_2$ concentration level is considered to be in the range of 400-440 ppm (a potentially high target level[3]), the peak year needs to occur between 2000 and 2020. Note that the lower the concentration target, the earlier the peak in concentration has to occur (more details are reported in Table 4). Due to the science behind climate change, there are a lot of uncertainties in trying to predict future atmospheric carbon content and it is difficult to assess the levels resulting from the reference scenario energy demand increases of the IEA. Based on a number of caveats, the energy demand increases of the reference scenario should be equivalent to $CO_2$ concentration levels in the range of 660-790 ppm, well above the stabilization target required to avoid the most detrimental impacts of climate change (IEA 2007

[2] toe/capita are tonnes of oil equivalent per capita.
[3] Scientists disagree on what the actual safe target level of CO2 concentrations should be. The UNFCCC has set 450 ppm as a "safe" target to avoid climate change danger. Others have put forward a lower target level of 350ppm, see for example Monastersky (2009) in Nature.

and IPCC 2007). Thus, mitigation actions are needed today. In the words of the IPCC report:

"...Many impacts can be reduced, delayed or avoided by mitigation. Mitigation efforts and investments over the next two to three decades will have a large impact on opportunities to achieve lower stabilisation levels. Delayed emission reductions significantly constrain the opportunities to achieve lower stabilisation levels and increase the risk of more severe climate change impacts. There is high agreement and much evidence that all stabilisation levels assessed can be achieved by deployment of a portfolio of technologies that are either currently available or expected to be commercialised in coming decades, assuming appropriate and effective incentives are in place for their development, acquisition, deployment and diffusion and addressing related barriers" (pg 19 and 20of the Climate Change 2007: Synthesis Report).

Although "low impact" energy sources are already available, they still play a minor role in meeting energy demand today. Currently, renewable energy sources[4] supply 13 percent of global energy demand, 10.1 percent from biomass and waste, 2.3 percent from hydropower and 0.5 percent from other renewables. Amongst the renewable energy sources, the largest share is taken up by hydropower for electricity generation and solid biomass for heat production, Table 3. The contribution of solar and wind energy is minimal.

This is even more surprising if we look at the technical feasibility of reverting to a less carbon intensive energy system. Azar (2005) shows that, a 400 ppm target for $CO_2$ concentrations, assuming high per capita energy use levels[5], is technically achievable. The solution lies in implementing energy efficiency policies that allow to reduce demand by 50 percent on the one hand, and an energy supply breakdown of 10 percent from fossil fuels, 20 percent from fossil fuel with carbon capture, 20 percent biomass and 50 percent from solar and wind, on the other. These figures do not sound unrealistic, but rely not only on a change in the energy mix, but also on a substantial increase in our ability to substitute for depletable resources.

[4] These include biomass and waste, hydropower, solar, wind, geothermal, tidal and wave energy. In IEA terminology, solar, wind, geothermal, tidal and wave energy are referred to as 'other renewables'.
[5] The main assumptions include emissions of 2 GtC/yr and a population of 10 billion using 200 GJ/yr/capita, equivalent to the level of an OECD person, and a timeline up to 2100.

In conclusion, the key is to act now, increase energy efficiency, diversify energy portfolios and improve our ability to use "low carbon" energy sources in place of the "high carbon" ones. The effort has to be twofold. In the short run, sources must be diversified and demand reduced by energy saving policies. In the long run though, as proposed by this research, energy portfolios need to change dramatically.

As mentioned, three papers constitute this thesis and the structure is as follows.

Papers I and II set up an intertemporal optimization problem in which the economy can use both a renewable and a depletable energy source in energy production. This part of the thesis builds on a large body of literature, whereby the innovative contribution is to explicitly introduce a renewable energy source and pollution in a Dasgupta-Heal type framework and study its role. The renewable and exhaustible energy sources are distinguished based on their contribution to pollution, cost, technology and availability.

In paper I we impose a specific set of constraints including a strong sustainability condition, Cobb Douglas production and exogenous technology. The strong sustainability condition requires the stock of pollution to be constant over time, equivalent to the argument that $CO_2$ concentrations in the atmosphere need to stabilize and remain constant thereafter. The set of assumptions allows us to obtain a closed form solution. We find that renewable resources are crucial for economic growth and that a restrictive condition on pollution needs to hold for the economy to be strongly sustainable. On the other hand, as the time horizon extends to infinity, the mere existence of renewable resources no longer guarantees strong sustainability.

In Paper II, we build on the model constructed in Paper I but release most of the assumptions made in the first paper, introducing endogenous learning by doing linked to the renewable energy resource and a wider range of consumption and production functional forms. We find conditions to achieve weak and strong sustainability. We find that renewable and depletable energy resources need to become highly substitutable and that substitution amongst resources and consumer flexibility are crucial in ensuring a weakly and strongly optimally sustainable economy.

In the context of recent commodity price surges, Paper III focuses on bioenergy and the impact of bioenergy developments on household welfare and food security in developing countries. Bioenergy will be an important energy source for some specific types of developing countries that have very limited energy access today and still rely heavily on the agriculture sector. Bioenergy is deemed as one of the causes of the price increases. When analyzing the effect of price increases on household welfare, the assumption of equi-proportionate price changes on the producer and consumer side is widespread in the literature. We show that such assumption does not allow for the analysis to be undertaken *ceteris paribus*. This negatively biases results and can lead to wrong policy indications. A methodological correction is proposed and sensitivity to the assumption is reported based on Peruvian and Tanzanian data. Conclusions on welfare impacts of price increases obtained under our proposed methodology are then presented for the case of Peru.

**Table 1: World primary energy energy demand.**

| **Energy Source** | **1980** | **2000** | **2005** | **2015** | **2030** | **2005-2030 (%)** |
|---|---|---|---|---|---|---|
| Coal | 1786 | 2292 | 2892 | 3988 | 4994 | 2.2 |
| Oil | 3106 | 3647 | 4000 | 4720 | 5585 | 1.3 |
| Gas | 1237 | 2089 | 2354 | 3044 | 3948 | 2.1 |
| Nuclear | 186 | 675 | 721 | 804 | 854 | 0.7 |
| Hydro | 147 | 226 | 251 | 327 | 416 | 2 |
| Biomass and waste | 753 | 1041 | 1149 | 1334 | 1615 | 1.4 |
| Other renewables | 12 | 53 | 61 | 145 | 308 | 6.7 |
| ***Total*** | *7228* | *10023* | *11429* | *14361* | *17721* | *1.8* |

Source: Reference scenario, IEA 2007.

**Table 2: Share by energy source (%)**

| **Energy Source** | **2005** | **2030** |
|---|---|---|
| Coal | 25.3 | 28.2 |
| Oil | 35.0 | 31.5 |
| Gas | 20.6 | 22.3 |
| Nuclear | 6.3 | 4.8 |
| Hydro | 2.2 | 2.3 |
| Biomass and waste | 10.1 | 9.1 |
| Other renewables | 0.5 | 1.7 |

Source: Reference scenario, IEA 2007.

**Table 3: Renewable energy contribution by type in 2006 for the world.**

| | Municipal Waste* | Industrial Waste | Primary Solid Biomass** | Biogas | Liquid Biofuels | Geothermal | Solar Thermal | Hydro | Solar Photovoltaics | Tide, Wave, Ocean | Wind | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Unit* | *GWh* | *GWh* | *GWh* | *GWh* | *GWh* | *GWh* | *GWh* | *GWh* | *GWh* | *GWh* | *GWh* | *GWh* |
| Gross Electricity Generation | 53571 | 12478 | 145002 | 24655 | 3675 | 59240 | 1061 | 3120614 | 2781 | 550 | 130073 | 3553700 |
| | 1.5 | 0.4 | 4.1 | 0.7 | 0.1 | 1.7 | 0.0 | 87.8 | 0.1 | 0.0 | 3.7 | |
| *Unit* | *TJ* | *TJ* | *TJ* | *TJ* | *TJ* | *TJ* | *TJ* | | | | | *TJ* |
| Gross Heat Production | 159988 | 93929 | 302610 | 11617 | 3072 | 11577 | 132 | | | | | 582925 |
| | 27.4 | 16.1 | 51.9 | 2.0 | 0.5 | 2.0 | 0.02 | | | | | |

Source: IEA, 2009 at www.iea.org.

**Table 4:**

| $CO_2$ Concentration (ppm) | $CO_2$-equivalent (ppm)* | Global mean temperature increase above pre-industrial level at equilibrium** ($^0C$) | Peaking year for $CO_2$ emissions | Global change in $CO_2$ emissions in 2050 (% of 2000 emissions) |
|---|---|---|---|---|
| 350-400 | 445-490 | 2.0-2.4 | 2000-2015 | -50 to -85 |
| 400-440 | 490-535 | 2.4-2.8 | 2000-2020 | -30 to -60 |
| 440-485 | 535-590 | 2.8-3.2 | 2010-2030 | +5 to -30 |
| 485-570 | 590-710 | 3.2-4.0 | 2020-2060 | +10 to +60 |
| 570-660 | 710-855 | 4.0-4.9 | 2050-2080 | +25 to +85 |
| 660-790 | 855-1130 | 4.9-6.1 | 2060-2090 | +90 to +140 |

* All greenhouse gases expressed in $CO_2$ –equivalent terms (adjusted for differences in radiative forcing); ** Based on "best estimate" of climate sensitivity.

Source: IPCC 2007 in IEA 2007.

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# Can renewable energy grant sustainable development in an oil fed economy?

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**Abstract**

Conditions for optimality and sustainable growth that can be reconciled with natural resource use have been discussed in the literature since the first oil shocks. In the wake of the climate change debate, the innovation is this paper is to add a renewable energy source to the Dasgupta-Heal type of framework, also including for pollution. This paper presents an intertemporal planning horizon problem in the presence of an exhaustible resource, a renewable resource and pollution. Pollution is introduced as a stock that causes disutility. The renewable energy source does not increase emissions and the amount available is not limited but, compared to the depletable resource, it is more costly. In this framework we investigate the growth rate of the economy and whether strong sustainability is achievable. We obtain a closed form solution and a stringent condition on pollution that has to be met in order achieve strong sustainability. This does not hold in the long run.

I would like to gratefully acknowledge Dr. Alessio D'Amato for all the meticulous supervision and Prof Withagen, Prof Sterner, Prof. Brown, Prof Roseta-Palma and EAERE 2008 participants for insightful comments and feedback. I am also thankful for the kind support of Prof. Castellucci, Prof. Marini and Prof. Scaramozzino. All errors are my own responsibility.

**Introduction**

As more countries develop and energy demand increases, the limits to growth are probably no longer those traditionally put forward in the literature. The most serious environmental threat for economic wellbeing today is climate change thus moving away from the traditional argument of resource scarsity toward that of clean air scarsity, or more specifically, the accumulation of pollution stocks in the environment.

Concern for the environment and implications for economic growth have been widely discussed by economists over time. Ever since the times of Malthus, there has been concern regarding resource availability and the limits to growth caused by an ever increasing population and the consequent pressure on natural resources. During the second half of the twentieth century, the concern for the environment started to move up the political and global agenda, beginning with Rachel Carson’s Silent Spring (1962) and Boulding’s Spaceship Earth (1966). The formidable demand on natural resource that had been witnessed during the Second World War, had sparked off the debate on resource scarcity, resulting in the famous study by Barnett and Morse (1963).The enquiry presented put forward the “compelling case that scarcity of the resources...did not yet, probably would not soon, and conceivably might not ever halt economic growth”. Although in the views of Barnett and Morse natural resources would not pose constraints to growth, in the early 1970s energy prices soared following the oil price shocks and the issue of energy supply became one of concern. Another group of academics responded and in 1972 the Club of Rome published its famous volume “Limits to Growth”, also known as the Meadows report. The view of the authors was more cumbersome and “predicted that such limits were fast approaching and that global society ignored them at its collective peril” (Pearce 2002, Simpson et al. 2004).

All this prompted trepidation regarding fossil fuel dependent economies and led to a symposium on the Economics of Exhaustible Resources (1974), at which formal academic analysis was presented including the studies by Solow (1974), Dasgupta and Heal (1974) and Stiglitz (1974) which analyzed different issues related to economies with single exhaustible resources.  The importance of the Hotelling’s rule for optimal exploitation of the non-renewable resource came back on the scene in conjunction with the message that, in order to achieve non-declining consumption, reinvesting resource rents in capital formation was crucial (Hotelling 1931, Hartwick, 1977). Although the concern for the environment and for how much human intervention it could withheld had been raised, the focus of the analysis discussed in the energy fora had mainly been on the limits to growth posed by fossil fuels, namely by the non-renewability of the resource as an essential input for production. Much of the research had concluded that through technical progress or reinvestment of the rents, economic growth was feasible.

In the following years a more holistic approach was put forward, arguing that natural capital had to be accounted for, defining the idea of sustainable development. In 1987 the United Nations Commission on Environment and Development (the Bruntland Commission) published the Brundtland report which stressed the importance of focusing on sustainable development, defined as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs.* Authors also distinguished between two levels of sustainability, namely weak and strong sustainability. Weak sustainability allowed for substitution between man-made capital and natural capital so that an economy could continuously accumulate physical capital at the expense of the natural capital without jeopardizing its sustainability. On the other hand strong sustainability focused on the stock of natural capital and claimed that this had to be maintained intact since the functions it performs cannot be duplicated by man-made capital (Pearce, Markandya, Barbier, 1989,Pearce 1993, Pezzey 1992).

The increase in CO2 concentrations of today have shown that limits to growth will likely not be due to lack of fossil fuel resources but to pollutants accumulation in the environment. In fact, as correctly argued by the authors cited, resource depletability has been overcome by technological innovation, but pollution damages have been an unexpected companion of fossil-fuel based economic development. The need to find alternative more sustainable energy sources for the world is becoming more and more a pressing issue and renewable energy technologies, such as wind and solar energy, are possible options that grant low or zero emission levels. The innovation in this paper is to build on the findings of Dasgupta and Heal (1974), Withagen (1998), Smulders (2000) and Pittel (2002) and add a renewable energy source to the framework.

There has been a large amount of research on renewable resources (see for example Chichilnisky et al 1998 and Titenberg 2005) but this has mostly been in the fields of forestry and fishery resources. The very nature of this type of renewable resources when compared to energy renewable resources are drastically different. Forestry and fishery resources are renewable in the sense that they can re-generate over time but they are available in a fixed amount which can be over harvested. Sun energy is potentially available in unlimited amounts, and likewise for wind energy (Azar 2005).

Literature has discussed some forms of clean alternatives in the form of technological innovation and back stop technology. Valente (2005) accounts for an exhaustible resource with some part of renewability deriving from a resource augmenting technology. The author finds that, in the case of constant returns to scale technology, optimal paths can be sustainable only if the social discount rate is less than the resource regeneration and augmentation rates. Schou (2000) analyses flow pollution, human capital and growth finding that economic growth is feasible but for the reasons given in Withagen (1995) and the issue at hand, namely climate change and the damages caused by pollution accumulation, we model pollution as a stock.

Building on the literature components discussed, this paper adds renewable energy to the modelling framework accounting for the pollution impacts of depletable resource use. More specifically, the paper will assess if a strongly sustainable path, as defined in Pittel (2002), is attainable when a renewable energy resource is available in addition to fossil fuel and if this availability is sufficient to grant long run sustainability. The two energy resources are differentiated based on cost, contribution to pollution, availability and technology. The representative agent gains from consumption but is damaged by pollution and society faces three constraints: scarcity of clean air, finiteness of the non-renewable energy stock and capital accumulation. The use of the non-depletable resource increases pollution although part of the pollution generated is naturally absorbed by the environment according to its absorption capacity. The standard constraint on the non depletable resources applies.

## The model

We now study the long run behaviour of an economy that seeks to maximize utilitarian welfare in a representative agent framework. Utility is a function of both consumption and pollution. The pollution stock accumulates over time, as, for example fossil fuel emissions do in the world's atmosphere. Society can use a renewable and a non-renewable energy resource which have key differentiating features, in the production of energy which is used to produce output. Society faces a constraint on pollution, a constraint on the depletable resources and a constraint on physical capital. Details of each building block are now provided.

## Renewable and depletable resources and production[1]

Energy is produced with a mixture of renewable, R(t), and non-renewable, Z(t), energy resources. As stated, contribution to pollution, availability of the resource, technology and cost are the four differentiating features of these environmental resources. We discuss these one by one.

As development has progressed, emissions from exhaustible resources have increased leading to expected severe impacts on the environment and human kind, while the emissions from renewable energy sources are potentially close to, if not zero. For the purpose of this model, the limit case scenario of zero emissions from renewable energy is considered. This entails that use of the depletable resource in energy production, and consequently in output production, contributes to the accumulation of the pollution stock.

By definition, depletable resources are available in a limited amount, namely the total amount of the resource is fixed. Consequently, as the resource is used, the stock of the depletable resource is exhausted. The renewable resource, on the other hand, by definition is available in an unlimited amount so that society faces no quantity constraint when using this resource.

Today, renewable resources cost considerably more than fossil fuel energy, taken to the extreme we could imagine that fossil fuels have a zero cost attached to them therefore we include the cost differential in a very simple way by assuming that the extraction costs of the

[1] Non renewable energy sources, also referred to as depletable, are those type of energy resources that are available in a fixed amount. This paper considers all types of fossil fuels in this category. On the other hand, renewable energy sources are not limited by availability. This paper mainly refers to solar energy and wind energy in this case.

depletable resources are zero while the renewable resource extraction costs are equal to a parameter g.

Finally, renewable energy, as opposed to the more traditional and well established fossil fuel technology, offers large technical progress potential due to the abundance of the resource and the little use society makes of it today. The innovation potential in the renewable resource entails that as time elapses the amount of output obtained per unit of renewable energy input would be increasing or equivalently that a smaller amount of renewable energy is required to obtain the same amount of final output. As outlined in Stiglitz (1974) and Valente (2005), we introduce exogenous technical progress in the form of resource augmenting technology., thus a 'technical progress' parameter, m, is included in the production function, augmenting the amount of renewable resource available, so that exogenous technical progress (ETP) takes the form of $m=e^{\omega t}$, where $\omega$ is the rate of exogenous technical progress.

Using a Cobb Douglas[2] production function is a necessary starting point in this case to be able to obtain a closed form solution. This is a standard intial assumption as for example in Schou (2000), Valente (2005) and Pittel (2002). Depletable and non depletable resources are used to generate energy, EN(t), through a Cobb Douglas production function

$$EN(t) = [Z(t)^{\beta}(mR(t))^{1-\beta}] \tag{1}$$

where $\beta$ is the share of the depletable resource.

The economy uses natural and physical capital, K(t), in production, where natural capital is used in energy production as shown in (1), in a Cobb Douglas functional form

$$F(K(t), Z(t), R(t)) = [K(t)^{1-\alpha} EN(t)^{\alpha}] = \left\{K(t)^{1-\alpha} Z(t)^{\alpha\beta}[mR(t)^{\alpha(1-\beta)}]\right\} \tag{2}$$

Assuming Cobb Douglas production functional forms entails that all inputs are essential in production, and more specifically, that both fossil fuels and renewable energy resources are

[2] Due to this, the standard restrictions deriving from a Cobb Douglas production function apply such as constant market shares and elasticity of substitution. A possible extension of this problem will be to introduce a CES production function.

needed to produce energy, thus $F(0,Z,R) = F(K,0,0) = 0$ [3]. The standard Inada conditions are satisfied.

In sum, renewable energy sources are a costly input into production while depletable resources, available at no cost, pollute and are thier in a fixed amount.

**Consumption**

Agents enjoy consumption but suffer from pollution (Smulders (2000), Pittel (2002)), therefore the welfare function of the representative agent is a function of both consumption and pollution, which causes disutilty, (3).

$$u(C(t),P(t)) = \ln C(t) + \ln(\overline{P} - P(t)) \qquad (3)$$

where C(t) is consumption and P(t) is the pollution stock[4], the amount of pollution that accumulates in the economy through use of Z(t) and utility is concave in both its arguments. Since consumers benefit from consumption, the marginal utility is positive, but at a decreasing rate $U_C > 0$ and $U_{CC} < 0$. On the other hand, pollution harms consumers so increasing pollution reduces utility, but at a decreasing rate $U_{PP} < 0$.. We take $\overline{P}$ to be the upper bound for pollution, namely the uppermost pollution that society can withstand, beyond which society would cease to exist. We assume that this threshold level of pollution can never be reached using all existing non-renewable resources at once[5].

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[3] The question of whether production with no fossil fuel input in the long run is possible, namely $F(K,0,R) = 0$, and within what time horizon this may possible remains an issue open for discussion and is not discussed here but is extensively treated in Dasgupta and Heal (1974).

[4] As outlined in the introduction, we consider pollution to be a stock since we refer to fossil fuels and the disutility generated through the consequent accumulation of carbon dioxide pollution. This is inline with the discussion in Withagen (1995).

[5] The assumption of separability in the utility function entails that the level of pollution has no impact on $U_C$ and viceversa that consumption has no impact on $U_P$. Separability is a standard assumption as in for example Pittel (2002).

**The pollution, resource depletion and capital accumulation constraints of the economy**

Society is constrained by the amount of pollution that accumulates, the limited availability of depletable resources and physical capital accumulation in its strive to maximize the welfare function of the representative agent over time.

As shown in Dasgupta and Heal (1974), Hotelling (1931) and Stiglitz (1974), the stock of exhaustible resource, S(t), decumulates by the amount used at time t by society, namely

$$\dot{S}(t) = -Z(t) \tag{4}$$

Two opposing effects impact the pollution stock, Pittel (2002): on the one hand the use of the non-renewable resource increases pollution, on the other, the environment is capable to absorb a portion of the pollution generated based on the environment's absorption capacity, $\gamma$. We take $\gamma$ to vary between 0 and 1, where 1 would mean that the environment has the capacity to absorb all emissions arising from the use of fossil fuels. Since renewable energy does not contribute to pollution it is not included in the pollution accumulation constrain and the net variation of the pollution stock is due to depletable resource use net of the absorption capacity of the environment, namely

$$\dot{P}(t) = Z(t) - \gamma P(t) \tag{5}$$

Capital is accumulated through net investment as standard including for renewable energy costs, g,

$$\dot{K}(t) = F[K(t), mR(t), Z(t)] - C(t) - gR(t) - \delta K(t) \tag{6}$$

where $\delta$ is the depreciation rate of physical capital

**The balanced growth path and the strong sustainability criterion**

Balanced growth is defined as the condition in which all variables grow at a constant rate and the rate of growth of output, consumption and capital are the same. We add a further constraint to this problem since we want to investigate the conditions under which Strong Sustainability holds. Strong sustainability is defined as the condition in which the stock of natural capital does not change and remains constant. As discussed earlier, in this paper we identify natural capital or the environment as green air due to the focus of the discussion on pollution and fossil versus renewable energy. Thus, according to Pittel (2002) and in the framework described in this paper, the minimum requirement for balanced growth to be strongly sustainable is that the stock of pollution stays constant over time, thus

$$\dot{P}(t) = 0 \Rightarrow \frac{\dot{P}(t)}{P(t)} = 0 \tag{7}$$

Therefore we look for the condition under which economic growth can be achieved using the depletable resource but keeping the pollution stock constant over time. In other words, the depletable resource would have to be used at the rate at which the environment can naturally counterbalance its use.

**The benevolent social planner's problem**

The maximization problem is that of a social planner that maximizes the present value of utility, as a function of consumption and pollution, subject to net emissions accumulation in the atmosphere, depletion of fossil fuel sources and net physical capital investment constraints. More specifically, the planner has to decide the optimal level of consumption, the optimal level of renewable resource use and how much of the exhaustible resource to optimally deplete. The structural form of the problem is as follow from (8) to (11):

$$\max_{\{C(t),R(t),Z(t)\}} \int_0^T u(C(t),P(t)) \cdot e^{-\rho t} dt \tag{8}$$

subject to

$$\dot{P}(t) = Z(t) - \gamma P(t) \tag{9}$$

$$\dot{S}(t) = -Z(t) \tag{10}$$

$$\dot{K}(t) = F[K(t), mR(t), Z(t)] - C(t) - gR(t) - \delta K(t) \tag{11}$$

where ρ is the rate of time preference and T is the end of the time horizon[6]. All quantities are positive and the initial conditions are as follows:

$$C(0) = C_0, K(0) = K_0, R(0) = R_0, P(0) = P_0, Z(0) = Z_0$$
$$C(t) \geq 0, K(t) \geq 0, R(t) \geq 0, P(t) \geq 0, Z(t) \geq 0$$

The current value Hamiltonian for this problem is as follow:

$$H(t) = U(C(t), P(t)) + \xi(t)[-Z(t)] + \lambda(t)[Z(t) - \gamma P(t)]$$
$$+ \mu(t)\{F[K(t), (mR(t)), Z(t)] - C(t) - gR(t) - \delta K(t)\} \tag{12}$$

where the shadow price of the exhaustible resource is ξ(t), the shadow price of pollution is λ(t), and the shadow price of net investment in capital is μ(t).

Deriving the Hamiltonian with respect to consumption we obtain:

$$\Rightarrow 1/C = \mu \tag{13}$$

which is the standard condition on utility according to which marginal benefits from consumption have to equal marginal costs along the optimal path or in other words the shadow price of consumption has to equal the marginal utility.

Under balanced growth and by loglinearizing and time differentiating the expression in (13) we obtain

$$\frac{\dot{C}}{C} = \frac{\dot{Y}}{Y} = \frac{\dot{K}}{K} = -\frac{\dot{\mu}}{\mu} \tag{13'}$$

[6] We thank C. Withagen and C. Roseta-Palma for pointing out the need to limit out attention to a finite time horizon in our framework.

so that along the optimal path, consumption, production and physical capital all grow at the same rate, ultimately equal to the opposite of the growth rate of the shadow price of consumption.

From the first order condition with respect to the renewable resource we find

$$F_R[K,R,Z] = g \tag{14}$$

or in other words, along the optimal path, the marginal benefit accruing from production thanks to an additional unit of renewable resource is equal to its cost. By loglinearizing and time differentiating this expression we find that in the long run the output and renewable energy resources' growth rates coincide:

$$\frac{\dot{Y}}{Y} = \frac{\dot{R}}{R} \tag{15}$$

The derivation of the current value Hamiltonian with respect to the non-renewable resource yields

$$F_z[k,R,Z] = \frac{\xi - \lambda}{\mu} \tag{16}$$

Interpretation of this result is less straightforward. This condition implies that the marginal cost of the depletable resource due both to its exhaustibility and to its contribution to pollution must equal the marginal (shadow) benefits related to the use of Z in production.

By loglinearizing and time differentiating the expression in (16) we obtain the growth rate of the non-renewable resource which is a function of the growth rate of shadow price of pollution and of the shadow price of the non-renewable resource as shown in (16')

$$\frac{\dot{Z}}{Z} = \frac{\dot{\lambda} - \dot{\xi}}{\lambda - \xi} \tag{16'}$$

To achieve optimality, a set of co-state equations as listed in (17), (18) and (19).

The costate equation for the stock of pollution P(t) is equal to

$$\frac{\dot{\lambda}}{\lambda} = \rho - (\frac{u_P}{\lambda} - \gamma) \tag{17}$$

which shows that the growth rate of the shadow price of pollution must equal the social discount rate net of a *pollution related factor*. The pollution factor is equal to the ratio of the marginal utility of pollution divided by the benefit from pollution net of the environment's absorption capacity.

The costate equation with respect to the stock of non-renewable resource is

$$\frac{\dot{\xi}}{\xi} = \rho \tag{18}$$

which is the standard Hotelling rule whereby the optimal use of the non-renewable resource is defined as the path along which the growth rate of the resource's shadow price is equal to the rate of time preference.

The costate equation with respect to the stock of physical capital K(t) is equal to

$$\frac{\dot{\mu}}{\mu} = \rho - (F_K(\cdot) - \delta) \tag{19}$$

Thus, along the optimal path, the rate of growth of the capital's shadow price is equal to the difference between the the discount rate and output's productivity net of its depreciation which, as standard, leads to the Ramsey Golden Rule for consumption.

By rearranging equation (9) we can write the rate of growth of the stock of pollution as follows

$$\frac{\dot{P}}{P} = \frac{Z}{P} - \gamma \tag{20}$$

As discussed above, under the assumption of balanced growth, a minimum requirement for strong sustainability is that the stock of pollution be constant or in other words that $\frac{\dot{P}}{P}$ equal zero. Using this definition of strong sustainability and applying it to (20), infers that the ratio of Z to P is constant and equal to γ. , For this to be true, namely for the ratio of Z to P to remain constant, the growth rates of P and Z have to be the same, and since we know that $\frac{\dot{P}}{P}$ is equal to zero it follows that also $\frac{\dot{Z}}{Z}$ has to equal zero, as shown in (21).

$$\frac{\dot{P}}{P} = \frac{\dot{Z}}{Z} = 0 \tag{21}$$

We now use this condition in equation in equation (16') also find that this implies that changes in the shadow price of pollution are equal to changes in the shadow price of the non-renewable resource over time, so we conclude that

$$\frac{\dot{\lambda} - \dot{\xi}}{\lambda - \xi} = 0 \Rightarrow \dot{\lambda} = \dot{\xi} \text{ if } \lambda \neq \xi \tag{22}$$

From the conditions listed above and through the manipulations described, a set of equations have been derived that describe the long run optimal paths in our economy.

$$\frac{\dot{C}}{C} = \frac{\dot{R}}{R} = \frac{\dot{K}}{K} = \frac{\dot{Y}}{Y} = -\frac{\dot{\mu}}{\mu} = (F_K(\cdot) - \delta) - \rho \tag{23}$$

$$\frac{\dot{P}}{P} = \frac{\dot{Z}}{Z} = 0 \qquad (24)$$

Equation (23) is the long run growth rate for the output, consumption, capital and the renewable resource, which coincide. Equation (24) is the long run optimal growth rate for pollution and fossil energy which is equal to zero. Therefore, along the optimal path, the economy will find it optimal to have output, consumption, capital and the renewable resource grow at a positive rate when the net marginal productivity of capital is larger than the social discount rate. On the other hand, for the optimal path to be strongly sustainable, the stock of pollution will remain constant, and in order to ensure this, the flow of the depletable resource will be constant as well over time.

Now, by log-linearizing the production function and using (23) and (24), we obtain the growth rate of the economy under exogenous technical progress, $\frac{\dot{Y}}{Y}^{EXO}$ and the strong sustainability condition:

$$\frac{\dot{Y}}{Y}^{EXO} = \frac{(1-\beta)}{\beta}\omega \qquad (25)$$

which leads to the following proposition I

*Proposition I: In the case of an economy that dislikes pollution and uses a depletable and renewable energy resource, the long run strongly sustainable growth rate of the economy will be higher the larger the share of renewable energy resources and the larger the rate of exogenous technical progress. The growth rate of the economy will decrease the larger the share of exhaustible resources.*

The result in (25) is in line with some of the results in the literature. The emphasis on technology is standard as in Solow (1953) and Stiglitz (1974). The innovation here is to see a clear role for the renewable resource in contributing to output growth. This exogenous growth rate shows that three factors influence the growth rate of the economy, namely the share of renewable resource, the share of exhaustible resources and the ETP rate. As the share of the renewable resources increase, the economy growth rate will increase. On the contrary, as the share of non renewables increases, the economy growth rate will decrease. Higher rates of ETP will have a positive influence on the economy's growth rate. Furthermore, if the ETP were to equal zero, ie. no technical progress, the growth rate of the economy would be constant and equal to zero. This is in line with the classical results of the Solow Model in which exogenous technical progress is the driver of the economy's growth. When $\omega=1$, or in other words when the rate of technical progress is equal to unity, (25) simplifies further. In this particular case the growth rate of the economy is equivalent to the ratio of the share of renewable resources to the share of depletable resources, thus as the share of renewable resources in the energy production increases the growth of the economy increases in the same proportion.

Conditions (23, 24, 25) define the sustainable balanced growth path: the longer the time horizon the smaller the amount of non-renewable resource available per period, and the stronger the substitution requirements between natural resources. This implies, intuitively, that in an economy with renewable and non-renewable resources, assuming an exogenous technical progress parameter, sustainable balanced growth in the long run is only possible if the two resources are almost perfectly substitutable (i.e. it is possible to produce output using only renewable resources). We can prove an even stronger result:

*Proposition* 2*: In an economy characterized by renewable and non renewable energy resources, Cobb Douglas technology and exogenous technical progress on the renewable resource, strongly sustainable balanced growth implies that pollution satisfies the following condition:* $P(T) = \overline{P} - \frac{1}{\rho \xi_0 e^{\rho T}}$

The proof for this can be attained through the set of transversality conditions that have to hold in order to ensure that the problem converges. As standard these conditions need to hold to ensure that as time draws in, either the stock of pollution or the capital asset will be exhausted, be it natural or physical, or that alternatively these assets will no longer have any value to society. The conditions are as follows:

$$e^{-\rho T} \xi(T) S(T) = 0 \qquad (26)$$

$$e^{-\rho T} \mu(T) K(T) = 0 \qquad (27)$$

$$e^{-\rho T}\lambda(T)P(T)=0 \tag{28}$$

Condition (26) is the transversality condition on the stock of depletable resource. In order for this condition to hold, at time T the stock of depletable resource is to be exhausted or the shadow price of the resource in T has to be zero. Based on (18) we know that the value of the resource can never be zero unless the initial value of it is zero. Thus in t=T the stock has to be exhausted for the transversality condition to hold.

Condition (27) has to hold for physical capital. Since we know from (23) that the shadow price of physical capital can never be zero, at time T the stock of physical capital will have to be fully exhausted for the optimality condition to be met.

Condition (28) is for pollution and states that when time elapses the discounted value of the stock of pollution has to be equal to zero, this can be due to either a final zero shadow price or the zero stock of pollution. Manipulation of (17), (18) and (22) yields the following for the shadow price of pollution

$$\lambda=\frac{u_p+\rho\xi_0 e^{\rho t}}{\gamma+\rho} \tag{29}$$

By substituting (29) in (28) when t=T we obtain

$$\left(\frac{u_p(T)+\rho\xi_0 e^{\rho T}}{\gamma+\rho}\right)e^{-\rho T}P(T)=0 \tag{30}$$

By deriving the utility function and manipulating (30) we obtain

$$P(T)=\overline{P}-\frac{1}{\rho\xi_0 e^{\rho T}}=\overline{P}-\frac{1}{\rho\xi(T)} \tag{31}$$

where $\overline{P}$ is the threshold maximum pollution level acceptable.

Since $\gamma + \rho > 0$ [7], condition (31) states that the terminal stock of pollution, and thus, following from the definition of strong sustainability, the level of pollution in the economy in the long run, must be less than the threshold level. The optimal "terminal" (i.e. time T) pollution level under the strong sustainability constraint will be higher when the initial value of the depletable resource is large and when ρ and/or T are large. In particular:

- as is reasonable, when individuals are more impatient, namely with a higher $\rho$, the sustainable level of pollution is higher.
- the longer the time horizon the more pollution in time T approaches the threshold level of pollution

Result summed up in Proposition 2 leads us to the following.

*Corollary 1: If the time horizon were to extend to infinity, a strongly sustainable balanced growth path is not attainable.*

The proof is straightforward: from (31) as $T \to \infty$ we get $P(T) = \overline{P}$. This shows that in the very long run the mere existence of both renewable and non renewable energy sources, do not allow an economy to be strongly sustainable. The violation of the transversality[8] conditions lead us to conclude that a sustainable balanced growth path is solely attainable if, in the long run, renewable energy resources can fully substitute depletable resources. The mere existence of the renewable resource and an exogenous technical change process are not sufficient for the economy to be sustainable in the long run[9].

[7] If γ+ρ=0, this would mean that either γ or ρ would have to negative but neither γ nor ρ can ever take on negative values so will condition will always hold.
[8] Note that if the time horizon of this maximization problem were to run from zero to infinity, it can be shown that the transversality condition on the pollution stock variable does not hold and thus the economy is unsustainable.
[9] If a constant zero pollution level were possible, renewable resources would have to substitute fossil fuels in the long run for sustainable development to be achievable.

***Discussion and conclusions***

We presented a model which accounts for the disutility caused by pollution and the option of exogenous technical progress linked to renewable energy in an economy constrained by limited non-renewable energy stocks and the negative effects of pollution on welfare. This society can choose whether to use a renewable energy resource or a depletable one. The renewable energy source does not cause emissions when used, is not constrained by being available in a limited amount and has technical progress potential, but, compared to the depletable resource, it is more costly. The framework used in the paper is that of a social planner that seeks to maximize social welfare under the a pollution, fossil fuel and physical capital constraint. In the model, as it stands, technological progress is introduced exogenously.

The findings in this paper bring to two main conclusions. On the one side, when overtly distinguishing between renewable and depletable energy resources, we show that economic growth is positively linked to the share of renewable energy and inversely proportional to the share of fossil fuels. Therefore policies that allow the size of renewable energy resources to grow will also foster economic growth. On the other hand, when looking for a strongly sustainable path, which in our set up implies a path along which pollution is constant (as for example would be the 'safe' stabilization target levels advocated by the IPCC 2007), optimal growth is only achievable if a condition on the admissible pollution level is met. Further, we show that strong sustainability turns out to be unfeasible if we extend the planning horizon to infinity.

Our model relies on a specific set of assumptions on functional forms in order to obtain a closed form solution and represents a departure point for further research. Nonetheless, we deem the implications of our results as relevant for the current energy related debate. Indeed, our results suggest that renewable resources, by themselves, might not be enough to guarantee that the economy evolve along a strongly sustainable development path.

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# Bioenergy and foodsecurity: Who benefits and who loses? The importance of the ceteris paribus assumption.

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**Abstract**

After a long period of decline, commodity prices have started to rapidly increase. The surge in these prices has been attributed to a number of causes, including the production of first generation feedstock to meet new biofuels demand. High commodity prices can be detrimental for households' food security, in fact the recent price surges have been heavily discussed in public fora and have been a serious cause for concern in developing countries. This paper aims to shed some light in the debate, in particular focusing on the assumption, which is widespread in the literature, of equi-proportionate price changes on the producer and consumer side; we show that such assumption implicitly embeds an assumption on marketing margins that negatively biases results and can lead to wrong policy indication. A methodological correction is proposed and sensitivity to the assumption is reported based on Peruvian and Tanzanian data. Conclusions on welfare impacts of price increases obtained under our proposed methodology are then presented for the case of Peru. Our results suggest that a judgement on the consequences of bioenergy production on food security should be made *case by case*.

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[1] The work presented in this paper is based on work with David Dawe undertaken within the Bioenergy and Food Security project of FAO supported by the German Government. All references are duly highlighted throughout the chapter.

## Introduction

Over recent years, modern bioenergy[2], defined as energy generated from biomass, has received a new wave of attention in developed countries in the wake of the worlds strive to mitigate climate change. Developing countries have long relied on traditional biomass for energy generation. Instead now the developed world and some developing countries are turning to a number of renewable energy sources, including solar, wind and biomass energy, to try and achieve the needed targets.

Bioenergy today is mostly biofuels where Brazil has a long tradition of use of bioethanol in its transport sector. Nevertheless the EU, US and Brazil are all planning to expand their use of bioenergy in the transport sector. The US is promoting an aggressive biofuels programme whereby, according to the Independence and Security Act (EISA) of 2007, production is to reach at least 36 billion gallons of biofuel production by 2022. The EU's biofuels' directive mandated biofuels at 5.75 percent by 2010 and, although struggling to achieve this target, has now set a 10 percent target by 2020 due to high reliance on imported oil and the need to achieve the climate change targets. Today, Brazil obtains between 30 and 40 percent of its automobile fuels from sugar cane-based ethanol and has recently added the National Programme for Biodiesel Production where biodiesel is to be blended initially at 2 percent and then at a mandatory blend of 5 percent by 2013. Currently, 90 percent of all ethanol production is equally shared by the US and Brazil and total production in 2006 was 40 million litres. Biodiesel production in 2006 reached 6.5 million liters, of which 75 percent is produced in the EU, mostly in Germany (World Watch Institute, 2008).

Rapidly developing countries and lesser developed countries are also looking at bioenergy and biofuels as an option to diversify their energy portfolio. China, heavily reliant on coal resources, and India are investigating a number of bioenergy options mostly due to the rapidly increasing energy demand coming with their rapid growth. A large number of developing countries from the African, Asian and Latin American region are looking into bioenergy and biofuels from sugar cane, palm oil, jatropha, cassava, etc. looking into the cost effectiveness of this option.

[2] Here bioenergy is intended as energy generated from first generation feedstock. The bioenergy portfolio of today also includes traditional biomass, still the main source of energy for households in least developed countries, second generation and third generation bioenergy. We do not discuss these here but focus on first generation bioenergy.

As the world turns to a number of new energy sources, the generation of bioenergy from energy crops has had a dual side to it. On the environmental side bioenergy had initially been promoted as a green energy source that could contribute to reduction of greenhouse gases, but today the perception of bioenergy has dramatically changed and the environmental effects are heavily debated (Kartha 2006, FAO 2008). From a developmental and social point of view, bioenergy has been heavily criticized too, where the discussion has even touched on issues like a second wave of colonisation. The crux of the matter will be the mode of development in order to ensure that bioenergy can aid rural development by increasing employment, income levels, access to energy and have a minimal impact on commodity prices and on natural resources (Kartha 2006, IFPRI 2006, FAO 2008).

One of the main reasons for which bioenergy has recently been heavily criticized has been due to the significant hike in food prices. Over the period 2006 to 2008, real international prices of food commodities have been increasing, completely reversing the trend in food prices witnessed since the 1970s. In fact for the first time since 1981, the real food price index of the Food and Agriculture Organization (FAO) of the United Nations surpassed the 150 mark. Many authors over the last months have debated the reasons for the soaring food prices listing a number of causes on the supply and demand side (Ref. Mitchell, Abbott, H., Von Braun and Headey). Supply side factors include production shortfalls due to weather shocks, high petroleum prices which are highly correlated with both fertilizer and producer prices. On the demand side authors have discussed factors such as changing diets in the major emerging economies, speculation on financial markets, trade policies and finally demand from the emerging biofuels market. Different authors have emphasized and given differing views on the root causes of the rapid increases in food prices. For what regards bioenergy, again there is a divergence in opinion on the amount by which biofuel demand may have contributed to the increase in food prices. Nonetheless all authors agree that this new market has contributed to the increase, discussing ranges from 10 to 75 percent depending on the author, the index and the commodity (Wiebe 2008).

Although this paper acknowledges this level of discussion and the contribution of new biofuels demand toward the surge in food prices, it will not attempt to go further into this aspect of the discussion so clearly put forward by Headey. We focus, instead, on the debate at the micro level, which is also touched upon in Headey, building on papers from a number of authors including Ivanic and Martin's (2008), Zezza et al.'s (2008), and Dessus et al.'s (2008).

The intricate nature of households in developing countries implies that they are mostly both producers and consumers at the same time. Due to this, higher prices can have both positive and negative consequences. Recently a number of authors have focused on the effects of the changes in food prices on households, on the poorer segments of the population and on poverty levels. More specifically we home in on the household level impacts and apply the methodology in line with current literature, but we make a strong case for an important change in part of the calculation which we show to have significant impacts on the final results, potentially leading to different policy directions. Specifically, we add to the existing literature by highlighting how developing countries might lose or gain from price changes, depending on their economic structure and conditions and, at the micro level, how conclusions change from urban households to rural households. We do this by applying a variation on the existing methodology, as developed in Dawe and Maltsoglou (2009).

The paper proceeds as follows. The following section describes the methodology currently used in the literature and how it relies on equi-proportionate price changes on the consumer and producer side. We then suggest an adjustment to the current methodology based on moving away from the marketing margins assumption embedded in assuming the equi-proportionate price change. Sensitivity to the assumption is shown based on Peruvian and Tanzanian data. The subsequent section reports results for the full range of commodities in the case of Peru. The final section concludes.

**Literature and current methodology**

The methodology used in this part of the analysis was initially set up by Deaton (1989), then followed by a number of empirical applications by other authors including Budd (1993), Minot and Goletti (1998) and, recently, Ivanic and Martin (2008) and Zezza et al (2008). In Deaton (1989), the author constructed an index called the Net-benefit ratio that allows to calculate the net effect for all producer-consumer households. In the analysis that follows we will mostly refer to the methodology as described in Minot and Goletti (2000).

Households can be both producers or consumers of an agriculture commodity and therefore price increases will affect different households in different ways based on whether a household is a net-consumer of the good considered or a net-producer. In fact for net producer households prices increases will be beneficial, while an increase in the price of the selected commodity will hurt households that are net consumers. Since households can be either producers or consumers of a good i, the impact of a price change on household welfare is decomposed into the impact on the household as a consumer of the good and the impact on the household as a producer of the good. The net welfare impact will be the difference between the two welfare effects.

In the case of consumer households, the impact of price changes is calculated based on the definition of compensating variation. Consumer's compensating variation (CV) is defined as the amount of money needed to compensate a consumer subject to a price change and restore utility to its original level3. Therefore if we consider two time periods, namely as initial time period 0 and a second time period 1, the change in CV between the two time periods is equivalent to the difference in the CV at time zero and new prices and CV at time zero and initial prices. In other words the CV change will be:

$$CV = e(p_1, u_0) - e(p_0, u_0) \tag{1}$$

where CV is the compensating variation, e(.) is the expenditure function, p is a vector of prices, u is utility, and the subscripts refer to before (0) and after (1) the price change. Manipulation of the expression defining compensating variation leads to the welfare effect for consumers:

[3] The classical measure of welfare change examined is consumer surplus, however CS is an exact measure of welfare change only in special circumstances.

$$\frac{CV}{x_0} = CR_i \frac{\Delta P_i}{P_{0i}} + \frac{1}{2}\varepsilon_{ii}^H \left( CR_i \frac{\Delta P_i}{P_{0i}} \right)^2 \qquad (2)$$

where Pi is the price of commodity i, $\varepsilon_{ii}^H$ is the own price Hicksian demand elasticity of commodity i, x0 is the intial income level, P0i,is the initial commodity price and CRi, the consumption ratio for the commodity, which is defined as the value of the commodity consumption as a proportion of income (or total expenditure). In this case the prices are on the consumer side.

The impact of price increases on households that are producers of the commodities considered is calculated by assessing the income change deriving from variation in profits at the two price levels.

$$\Delta x = \pi(p_1, w_0, z_0) - \pi(p_0, w_0, z_0) \qquad (3)$$

Manipulation of this expression yields:

$$\frac{\Delta x}{x_0} = PR_i \frac{\Delta P_i}{P_{0i}} + \frac{1}{2}\varepsilon_{ii}^S \left( PR_i \frac{\Delta P_i}{P_{0i}} \right)^2 \qquad (4)$$

where PRi is the production ratio of commodity I defined as the ratio between the value of production of i to income (or total expenditure), $\varepsilon_{ii}^S$ is the own price supply elasticity of commodity i, and prices are the producer prices.

The overall second order net welfare impact, $\frac{\Delta w^2}{x_0}$, is obtained from the difference between (4) and (2) as shown below in (5)

$$\frac{\Delta w^2}{x_0} = PR_i \frac{\Delta P_i^p}{P_{oi}^p} + \frac{1}{2}\varepsilon_{ii}^S \left( PR_i \frac{\Delta P_i^p}{P_{oi}^p} \right)^2 - CR_i \frac{\Delta P_i^c}{P_{oi}^c} - \frac{1}{2}\varepsilon_{ii}^H \left( CR_i \frac{\Delta P_i^c}{P_{oi}^c} \right)^2 \qquad (5)$$

If we set the demand and supply side elasticities equal to zero, thus ignoring consumer and producer side response to price changes the immediate welfare impact on households is calculated as

$$\frac{\Delta w^1}{x_0} = PR_i \frac{\Delta P_i^p}{P_{oi}^p} - CR_i \frac{\Delta P_i^c}{P_{oi}^c} \tag{6}$$

where $\frac{\Delta w^1}{x_0}$ is the first order approximation of the net welfare impact on producer and consumer households deriving from a price change in commodity i.

When calculating the short term impacts of price changes on household welfare based on (6), a natural choice in the literature has been to use equal percentage change for both farmers and consumers Nevertheless this choice comes with an underlying assumption on marketing margins. This issue has been discussed in some papers (Minot and Goletti (1998) make clear reference to marketing margins) but potentially overlooked or underestimated in others. With the aid of two simple numerical examples we start by illustrating how assuming equal or different price changes on the producer and consumer side has very different implications on the underlying assumption on marketing margins. Since the scope of the current analysis is on the impact of commodity price changes on household welfare ceteris paribus and not on the joint effect of food price and marketing margin changes, we propose that consumer and producer price changes cannot be taken to be equal. By adopting this point of view, we propose a simple methodology that can be used when only one side of the price change is set, be it the consumer or producer side. Finally we show with applications to two datasets that the two assumptions have very different implications on the final results of the welfare analysis and therefore are key in this type of analysis and cannot therefore be overlooked.

**Illustrating the assumption on marketing margins and how it matters**

We set up two examples in order to illustrate the marketing margins assumption embedded in the assumption on price changes. We will refer to Case 1 as the case that is in line with the literature, i.e. assuming the increase in producer and consumer prices to be the same. In case 2 on the other hand, we allow for the consumer and producer price changes to be different.

- *Case 1: Producer and consumer prices increase by the same amount*

Let us consider two points in time 0 and 1 and start with an initial scenario where the producer price of a good is 10, while at retail level the price is 20. In this simple numerical example we abstract from any specific currency for ease of exposition[4]. This is the case where consumer and producer price changes are set to be the same, for example 20 percent (Figure 1).

**Figure 1: Case 1: Consumer and producer prices change by the same percentage.**

| Time | Producer price | Marketing Margin | Consumer price |
|---|---|---|---|
| 0 | 10 | | 20 |
| Price change | 20% | | 20% |
| 1 | | | |

| Time | Producer price | Marketing Margin | Consumer price |
|---|---|---|---|
| 0 | 10 | **10** | 20 |
| Price change | 20% | | 20% |
| 1 | **12** | | **24** |

| Time | Producer price | Marketing Margin | Consumer price |
|---|---|---|---|
| 0 | 10 | 10 | 20 |
| Price change | 20% | **20%** | 20% |
| 1 | 12 | **12** | 24 |

Having these prices in time 0 is equivalent to a marketing margin of 10. In time 1 prices have increased by 20 percent so the producer price will have gone up to 12 and the consumer price

[4] Furthermore note that in practice all prices would need to be expressed in comparable units accounting for any adjustment that might be necessary due to the specific nature of the crop at hand also ensuring that the same quality or processing level of the commodity is being referred to. For example rice can be expressed in paddy or in actual rice production, high and low quality and need to include for the milling ratio when moving from paddy to rice.

to 24. Now the marketing margin is 12. Therefore the marketing margin has also increased by 20 percent and gone to 12. What this shows is that *when price changes on the consumer and producer side are assumed to be the same, this implies that also marketing margins increase by the same percentage change* of 20 percent. This would be equivalent to assuming that there is a third group of players in this economy, traders, that gain from the price increases and to which part of the income increase has to be redistributed.

- *Case 2*: *Producer and consumer prices increase by different percentages and marketing margins are assumed to be constant.*

In this case, Figure 2, we assume that producer and consumer price changes are no longer taken a priori to be the same. As before, we start by taking an example in which, at time 0, the producer price is equal to 10 and the consumer price is equal to 20. In this case we only assume what the price increase on the producer side is and we take it to be 20 percent. Based on the prices at time 0 the marketing margin is equal to 10. Since we assume that marketing margins remain constant, at time 1 the difference between the producer and consumer prices will still be equal to 10. We assume that the percentage price change is on the producer side and take it to be 20 percent as above.

**Figure 2: Case 2: Consumer and producer prices change by different percentages.**

| Time | Producer price | Marketing Margin | Consumer price |
|---|---|---|---|
| 0 | 10 | 10 | 20 |
| Price change | 20% | | |
| 1 | | 10 | |

| Time | Producer price | Marketing Margin | Consumer price |
|---|---|---|---|
| 0 | 10 | 10 | 20 |
| Price change | 20% | | |
| 1 | **12** | 10 | **22** |

| Time | Producer price | Marketing Margin | Consumer price |
|---|---|---|---|
| 0 | 10 | 10 | 20 |
| Price change | 20% | **0%** | **10%** |
| 1 | 12 | 10 | 22 |

Based on this at time 1 we will have a producer price of 12 and a consumer price of 22. This shows how, in the case of no change in marketing margins, producer and consumer price changes are different. Furthermore, due to the lower absolute levels of the farmgate prices, producer price changes will be larger price changes at the retail level.

The truth of the matter is that in reality we do not know if the increase in the marketing margins is the same as the producer and consumer price change, if it is zero or if it lies somewhere in between. As shown in Table 1 where price changes for the period 2006-2008 are listed for the main food crops in the case of Peru, movements in price changes are complex and the result of a multitude of effects. Nevertheless if the scope of the analysis is to investigate the impact of increasing food prices on household welfare *ceteris paribus*, marketing margins have to be held constant and therefore we need to position ourselves in a Case 2 scenario.

For the Case 2 setting we present a relatively simple mathematical derivation that correctly describes the relationship between producer and consumer price changes in the case of constant marketing margins[5]. We start by setting consumer prices, $P_C$ , equal to producer prices, $P_P$ , plus a marketing margin, M:

$$P_C = P_P + M \tag{7}$$

When taking differences this yields:

$$dP_C = dP_P + dM \tag{8}$$

The assumption of constant M gives:

$$dP_P = dP_C \tag{9}$$

We then divide both sides by $P_P$ and multiply the right hand side by $P_C/P_C$:

[5] This methodology presented in this section is based on Dawe and Maltsoglou (2009).

$$\frac{dP_P}{P_P} = \frac{dP_C}{P_F} \cdot \frac{P_C}{P_C} \tag{10}$$

Which can be re-written as:

$$\frac{dP_P}{P_P} = \frac{dP_C}{P_C} \cdot \frac{P_C}{P_P} \tag{11}$$

This shows that the percentage change in producer price equals the percentage change in consumer price multiplied by the ratio of the consumer to the producer price. Therefore if we were to assume a percentage price change for the producer price of 10 percent, in order to calculate the change on the consumer side we would be missing the producer to consumer price ratio. There are several sources of data that could be used to obtain the producer to consumer price ratio in (11) for the specific commodity in question. One possibility is to use the survey data, provided it has data on either prices or quantities (data on expenditures and quantities can be used to calculate an implicit price). Another possibility is secondary data on prices, although one must be careful that such data are nationally representative and pertain to the same quality at farm and retail levels. If secondary data on farm prices are not available, and the survey does not have data for either prices or quantities, it is also possible to use macro level data (production, imports, exports, stock changes) coupled with expenditure and revenue data from the survey to obtain an estimate of relative producer and consumer prices, as we will now show.

In a self-sufficient economy, consumer expenditures (CE) on the staple food will equal production value (PV) plus marketing costs (MC) (all of these numbers are in units of local currency), as shown in (12).

$$CE = PV + MC \tag{12}$$

Which is equivalent to:

$$P_C \cdot Q_C = P_P \cdot Q_P + MC \tag{13}$$

where $Q_P$ and $Q_C$ represent the quantity of production and the quantity of consumption, respectively (which are equal under self-sufficiency).

Divide through by $(P_C \cdot Q_C)$ to obtain:

$$\left(\frac{P_C \cdot Q_C}{P_P \cdot Q_P}\right) = 1 + \left(\frac{MC}{P_P \cdot Q_P}\right) \qquad (14)$$

Using $Q_C = Q_P$ (the units must be identical) we can re-write (14) as follows:

$$\left(\frac{P_C}{P_P}\right) = 1 + \left(\frac{MC}{P_P \cdot Q_P}\right) \qquad (15)$$

Using $(P_C \cdot Q_C) = PV$ and $MC = CE - PV$ on the right hand side gives:

$$\left(\frac{P_C}{P_P}\right) = \left(\frac{CE}{PV}\right) \qquad (16)$$

Thus the ratio of prices is equal to the ratio of CE to PV in a self-sufficient economy. In an economy that is a net importer of the staple food, consumer expenditures must first be scaled down by the ratio of domestic production to domestic consumption (which will be less than one); this gives consumer expenditures on domestically produced staple food (we assume that imports and domestically produced food are of identical quality), which can then be divided by production value PV to obtain the price ratio. In an economy that is a net exporter of the staple food, consumer expenditures should be scaled by the same ratio, which now however will be greater than one. Thus, in either case:

$$CE' = CE \cdot \left(\frac{Y^D}{C^D}\right) \qquad (17)$$

$$\left(\frac{P_C}{P_P}\right) = \left(\frac{CE'}{PV}\right) \qquad (18)$$

where $Y^D$ and $C^D$ are domestic production and consumption respectively.

This reduces to equation (18) in the case of self-sufficiency, but it also holds for the more general case of net importers and net exporters.

**The effects of the marketing margins assumption on welfare calculations**

Having illustrated the differences in the underlying assumptions of Case 1 and Case 2 we now apply the two methods to household level data to illustrate the implications that these assumptions have on the household level welfare impact assessments. We present the case of Peru and the case of Tanzania and two different crops as a robustness check to show that the analysis is neither crop nor country specific. We illustrate the rationale for the crop selection and an initial overview of the macroeconomic trade flows of these commodities.

The list of commodities is selected based on the calorie contribution of commodities to household diets in the countries. Based on this list of commodities we start by looking at macro economic trade flow data to gain an initial understanding of the potential impact of price increase at the country level. Price changes can affect a country in different ways depending on whether the country is a net importer or a net exporter of a selected commodity. In fact, at the macro level if we consider the country as a single entity, an increase in the price of a selected commodity will have a negative impact on the country if the country is a net importer of that good. If, on the other hand, the country is a net-exporter of a commodity the country will benefit from the price increase[6]. It is important, therefore, to start off with the macroeconomic trade flow data, a relevant yardstick.

Based on calorie contribution shares we rank the most important food crops for the case of Peru, Table 2. This shows that the five most important staple crops are rice, sugar, wheat, potatoes and maize and together provide 60 percent of total calories to households in Peru. As shown by Table 3, Peru is nearly self-sufficient in rice and potato production but heavily relies on imports for wheat, maize and sugar for domestic consumption. In the case of Peru we use national household level data from the Enquesta Nacional de Hogares (ENAHO) in 2006. This dataset is nationally representative and collected annually by the national statistics institute (Instituto Nacional de Estadistica (INEI)) in Peru. The 2006 ENAHO survey covered a total of 20,577 households, 65 percent of which come from urban areas, while the remaining 35 percent live in rural areas.

[6] This is an analogous rational as that used at the household level where a net-importing household would be equivalent to a net-consumer household that will be hurt by the price increase while a net-exporter household will be equivalent to a net-producer household which will benefit from the price increase.

According to the calorie ranking, the most important food crops for the case of Tanzania are maize, cassava, rice, wheat and sorghum Table 4. These five crops together provide 65 percent of total calories to households. Tanzania is mostly self-sufficient in maize and rice production, self-sufficient in cassava and sorghum and largely reliant on imports for wheat consumption, Table 5. In the case of Tanzania the equivalent national household dataset, the Household Budget Survey, does not report data on agriculture income to the level of detail needed. Due to this we revert to a smaller but more detailed dataset that surveys rural households in the regions of Ruvuma and Kilimanjaro in Tanzania. The dataset covers 892 households in Ruvuma and 957 households in Kilimanjaro.

As discussed in Dawe and Maltsoglou (2009), in addition to introducing an adjustment for constant marketing margins we also include for differences in processing factors depending on the crop at hand. In order to be able to focus solely on the effect of the marketing margin assumption in this section we discuss two crops from within the country lists discussed above but that undergo less processing between the producer and consumer levels7. Therefore we discuss the case of potato in Peru first and report results for the whole country and for the rural areas. For Tanzania we illustrate the case of cassava in the Ruvuma region. The Ruvuma region is one of the four main agriculture regions of Tanzania and a big producer of cassava but also one of the poorest areas of the country that suffers from severe lack of infrastructure. The results are presented by quintile.

Figures 3 and 4 show the welfare changes across quintiles for two separate simulations, Case 1 and Case 2 for potatoes. Figure 3 is for the entire country, while Figure 4 is for rural areas only. In Case 1 both farm and retail prices increase by 10 percent. Case 2 sets a 10 percent price change on the producer side and calculates the consumer level price change of 4.9 percent based on the approach presented using the survey and macro data.

In the case of potatoes, Peru is mostly self-sufficient which means that approximately all domestic demand is met with domestic supply. For the whole population, Figure 3 shows that, for Case 1, all quintiles lose. In Case 2, on the other hand, some quintiles win from an increase in prices while others lose. The results reported in Case 1 do not seem plausible

[7] For more details on the actual processing factors please refer to Dawe and Maltsoglou (2009). An example of a crop that undergoes more processing is that of wheat. Wheat is produced as wheat but consumed as flour, bread or pasta to name a few examples of its subproducts.

based on the net import status of Peru, while Case 2 results indicate that the richest quintiles in the economy that are mostly net consumers of potato, are the ones hurt by the price increase.

When we move to the rural areas subsample the picture becomes even more stark. Figure 4 shows that, for Case 1, four of the five quintiles lose, and the third quintile experiences a very small net gain. In contrast, for Case 2, all quintiles are winners from a price increase and the effects are much larger in this case compared to the previous one. That rural households in Peru can lose from a price increase is very surprising given Peru's near self-sufficiency. This is most likely driven by the fact that Case 1 assumes an increase in marketing margins that is simply withdrawn from the income of the country.

Another key difference between Cases 1 and 2 in the case of potatoes can be seen in the results for the first quintile, the poorest segment of the population. Under the Case 1 scenario, the poorest quintile is harmed substantially by a price increase for potatoes (with only quintile 4 being harmed more, but only slightly more). Under the Case 2 scenario, however, the poorest quintile benefits the most from a price increase. Thus, use of equi-proportionate price increases at farm and retail levels leads to drastically different policy outcomes.

In Figure 5 we illustrate the case of the effects of a price increase on rural household welfare in the Ruvuma region of Tanzania. For case 1 all quintiles in the region lose from a price increase in Cassava. On the other hand, for Case 2, some households lose while the top two quintiles benefit from the price increase, which seems more plausible in line with the importance of this crop in the country but the actual severe infrastructure problems of the region. Again we find stark differences between the two sets of simulation.

These comparisons between Cases 1 and 2 show that it is important to make clear assumptions about marketing margins, and that failure to do so can have important effects on the results, both in terms of whether a given quintile wins or loses from a price increase, but also in terms of relative effects across quintiles.

In the next section, based on the approach adopted in Case 2, we present full results for the selected commodities in the case of Peru (for the data reasons given the full analysis for the whole of Tanzania is not possible).

**Welfare impacts in the case of Peru based on the Case 2 methodology.**

The actual aim of this type of analysis is to be able to assess which segments of the population may be hurt and are most vulnerable to the price increases, essential information for sound policy design. We now turn to the case of Peru and run the complete analysis based on the amended methodology outlined. Depending on the crop at hand and with the use of the survey and macroeconomic data, we assume a 10 percent price increase on the producer side and calculate the consumer side price change. In addition to this, depending on the nature of the crop, we allow for some processing adjustment factors as previously discussed. The analysis is run by quintile and distinguishes between urban and rural households. In order to account for differences in living costs we deflate urban income and expenditure to bring it in line with rural income and expenditure levels[8].

Figure 6 illustrates the effects of a 10 percent price change of rice on households in Peru and shows the impacts for the whole country, for the urban households and for the rural households. For the country as a whole, a 10 percent increase in the price of rice at the farmer's level will hurt the poorest segment of the population. The picture changes when distinguishing between urban and rural households. In urban areas, increases in the price of rice will hurt all segments of the population. The larger impacts will be felt by the two bottom quintiles and the fourth quintile. In rural areas, increases in the price of rice can have some positive effects, where the price increase will hurt the bottom quintile but will be positive for the second lowest quintile and the top two quintiles. Since Peru is approximately self-sufficient in the production of rice this result seems to be in line with the macrodata of the economy showing that some will gain from the price increase while others will lose. Depending on the focus of the policy to be implemented and the potential target group under consideration, policy indications would be different. For example, in some cases we find that the lower quintile benefits from the price increase while the wealthier population segment loses. If the focus of the policy is poverty reduction and monitoring of vulnerable groups, this price increase would overall be beneficial. On the other hand, if the price increase were to harm the poorest population segment, interim policy measures might be needed to in the short run to dampen the negative effects.

[8] This is done by scaling the urban income and expenditure variables by the ratio of urban to rural poverty line

Figure 7 illustrates the effects of price changes for the case of sugar. Overall, welfare impacts appear to be a lot smaller compared to the case of rice. For the country as a whole the impacts of the price increase are minimal. Households in urban areas will lose from the price increase and the most severely hit will be the bottom income quintile. Rural households will benefit from the price increase, especially the third quintile, but also the first and second. Therefore, increases in the price of sugar can have a detrimental effect on the poorest segment of the population in the urban areas but can benefit the poor in the rural areas.

Figure 8 shows the effects of a 10 percent increase in the price of wheat for households in Peru. As discussed in the previous section, Peru is a heavy net importer of wheat and this is validated by these results. All households in Peru lose from an increase in the price of wheat, and this trend is born out both in the urban and rural areas. Amongst the poorest segment, households in urban areas are hit more than household in rural areas.

Figure 9 shows the case of potato. For the country as a whole, the impact in the price increase overall is largely positive, whereby the bottom two quintiles bear the largest benefit from the price increase, while the top two are slightly hit, the top quintile more so. From the urban households perspective the impacts are different. The price increase is beneficial only for the poorest households, while all other quintiles are hurt. In rural areas all households benefit from the price increase, and the benefits to the bottom two quintiles are the largest. The picture depicted is inline with Peru’s self sufficiency status in the case of potato production.

Figure 10 reports on the effects of a 10 percent price change in the price of maize. For the country as a whole the bottom quintile will benefit from the price increase, while all other quintiles will lose, and the two top quintiles will lose the most. All urban households will be hurt by the price increase, but the top three quintiles will suffer the most. All households in rural areas will gain from the price increase, the highest benefit will be felt by the bottom quintile.

The full analysis shows that impacts of price increases depend on the nature of the commodity at hand, the general macroeconomic position of the country in the commodity’s production and are heavily tied to the dual nature of households that are both consumer and producers of goods, where urban households generally are net consumers of products while rural households can be net producers. Adopting the price change calculations proposed, allows to capture the dual nature of the household and to distinguish between potential beneficial and detrimental effects of price changes across quintiles and commodity. This will be essential for more accurate policy design that will ensure the benefits to net producing households of price increases are captured, while sheltering the most vulnerable households.

**Conclusions**

A number of papers recently have seen in bioenergy one of the root causes of the surge in food prices. This paper moves from the discussion of the causes of food price increases to the micro level impacts of such increases and elaborates on the methodology used to assess the household level impacts. We show that assuming equi-proportionate price changes on the consumer and producer side implicitly embeds an assumption on marketing margins that proves to be critical in this type of analysis. Moving away from the equi-proportionate change in consumer and producer prices is crucial in ensuring that marketing margins do not change and that effects of price changes on household welfare can be analyzed *ceteris paribus*.

In fact, we find that failure to acknowledge the implicit marketing assumptions embedded in the equi-proportionate price change leads to a bias towards finding negative impacts of higher food prices. This is true for both datasets that are analysed in the paper. We therefore suggest a simple alternative approach to calculate the percentage price change based on setting either the producer or consumer side of the price change equal to a predefined amount and calculating the other side of the price change with the aid of survey and macroeconomic data. Using the changed methodology, and running the analysis by commodity, allows to show how general conclusions in the existing literature to date, can lead to wrong policy conclusions and indications (Zezza et al. (2008) and Ivanic and Martin (2008)).

Allowing the potential net producer households to benefit from the price increases will be essential in the cases of less developed countries where the agriculture sector still contributes a large share of the GDP, employs large segments of the population and has been targeted as playing a key role in poverty reduction in this type of economies (as would be the case in countries like Tanzania for example). In this context it will be essential that more accurate policy design ensures that net producing households capture the benefits of price increases, while sheltering the most vulnerable households. What will then be key is ensuring that households' supply response can take place in countries where the agriculture sector is still riddled with problems of lack of investment and consequent low productivity as clearly put forward in Von Braun (2008). This will require some form of government investment or joint investment programmes that ensure that infrastructure and technical capacity (from low to high level) are increased.

**Table 1: Percent changes in farmgate, wholesale, retail prices by commodity between 2006-2008 in Peru-**

| Farmgate prices 2006-2008 (%) | Wholesale prices 2006-2008 (%) | | Consumer prices 2006-2008 (%) | |
|---|---|---|---|---|
| Rice | Rice low wholesale | | Rice low consumer | Rice high consumer |
| 45.4 | 37.3 | | 9.6 | 6.8 |
| | White sugar | Red sugar | White sugar | Red sugar |
| | -37.1 | -55.7 | -33.9 | -44.8 |
| White maize | | | White maize | |
| 29.5 | | | 18.3 | |
| Wheat | Hard wheat | Wheat flour | Peeled wheat | Wheat refined |
| 9.3 | 17.9 | 32.2 | 6.9 | 12.9 |
| Potato | Potato | Yellow potato | Potato | Yellow potato |
| -7.4 | -16.0 | 10.1 | -14.3 | 7.2 |

Source: Calculation of the author based on prices collected by National Institute of Statistics (INEI).

**Table 2: Calorie contribution by commodity for Peru.**

| Ranking | Commodity | Calorie share |
|---|---|---|
| 1 | Rice (Milled Equivalent) | 19.2 |
| 2 | Sugar (Raw Equivalent) | 14.0 |
| 3 | Wheat | 13.6 |
| 4 | Potatoes | 7.6 |
| 5 | Maize | 5.2 |

Source: FAOSTAT

**Table 3: Macroeconomic trade flows for main food crops in Peru.**

| Commodity | Production (1000 MT) | Import (1000 MT) | Export (1000 MT) | Net-Importer (%)* |
|---|---|---|---|---|
| Rice | 1,600 | 71 | 20 | 3 |
| Sugar | 760 | 265 | 33 | 25 |
| Wheat | 175 | 1,332 | 44 | 84 |
| Potatoes* | 3151 | 98 | 0 | 3 |
| Maize | 1,400 | 1,528 | 8 | 53 |

* Calculated as the ((Imports-exports)/consumption)
Source: Average between 2004 and 2006, USDA

**Table 4: Calorie contribution by commodity for Tanzania.**

| Ranking | Commodity | Calorie share |
|---|---|---|
| 1 | Maize | 33.4 |
| 2 | Cassava | 15.2 |
| 3 | Rice (Milled Equivalent) | 7.9 |
| 4 | Wheat | 4.0 |
| 5 | Sorghum | 4.0 |

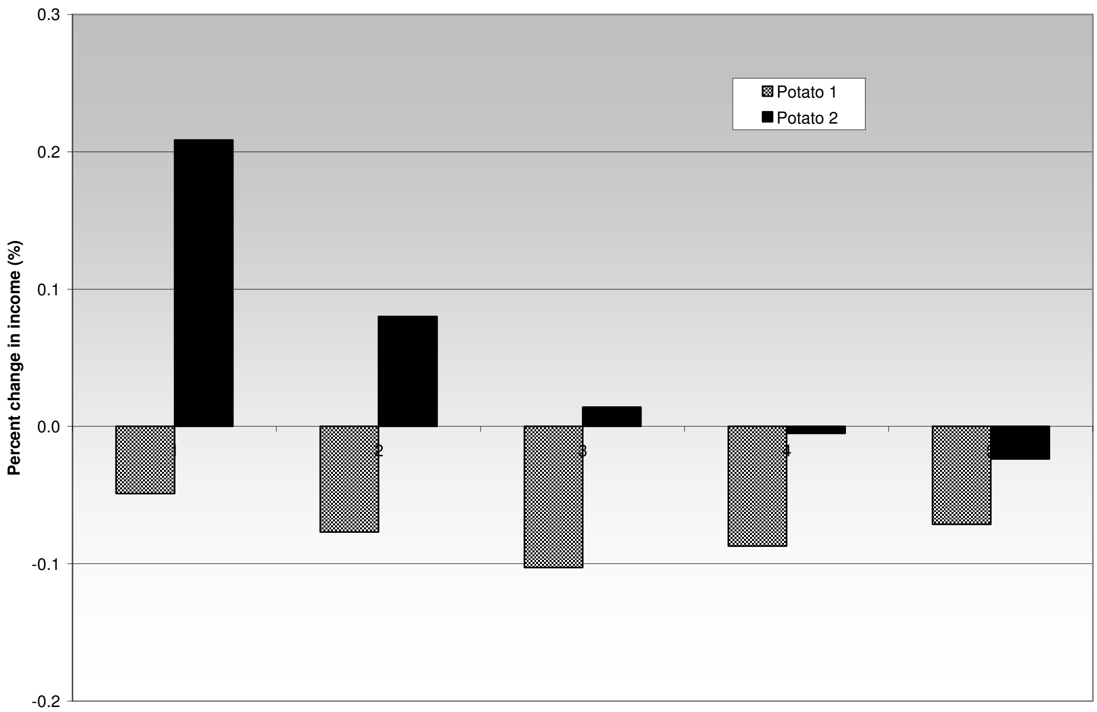
Source: FAOSTAT

**Table 5: : Macroeconomic trade flows for main food crops in Tanzania.**

| Items | Production quantity (MT) | Import quantity (MT) | Export quantity (MT) | Net-importer | Net-exporter |
|---|---|---|---|---|---|
| Maize | 3,288,000 | 44,500 | 98,985 | - | 0.02 |
| Cassava | 7,061,867 | 0 | 839 | - | - |
| Rice | 957,000 | 18,846 | 3,717 | 0.02 | - |
| Wheat | 87,133 | 254,732 | 36,428 | 0.71 | - |
| Sorghum | 653,644 | 0 | 0 | - | - |

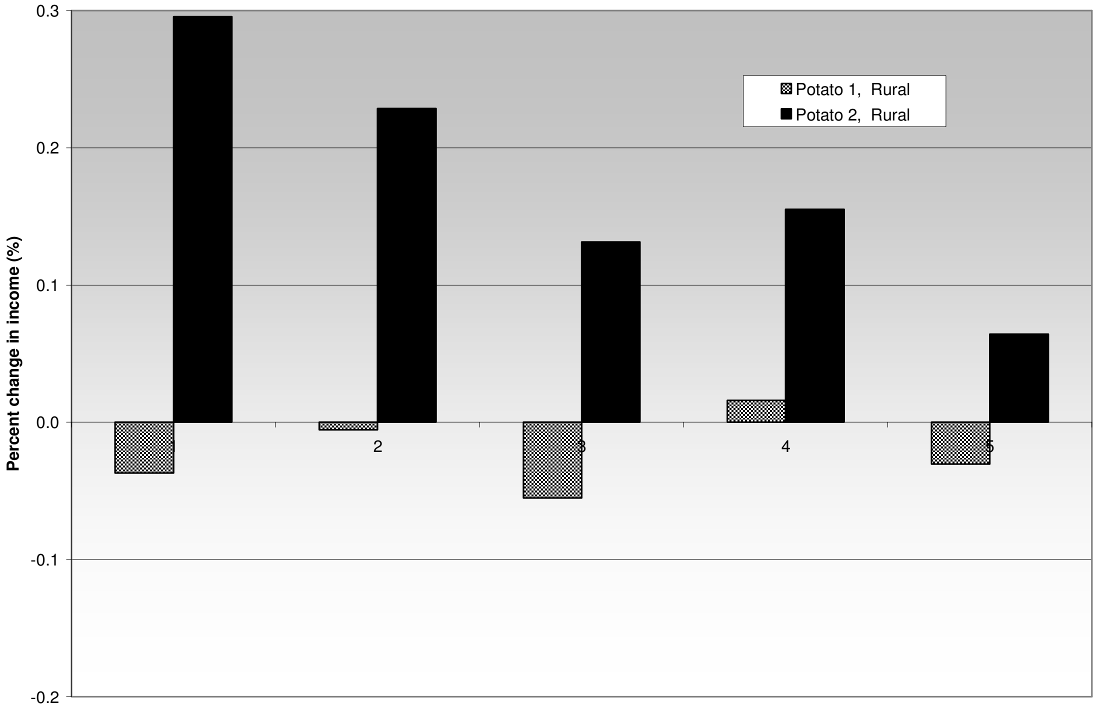
Source: FAOSTAT, USDA and Ministry of Agriculture of Tanzania, all data are reported for the period 2002 to 2005.

**Figure 3: Sensitivity analysis to Case 1 (Potato 1) and Case 2 (Potato 2) for household level welfare impacts in the case of potato in Peru for the whole sample.**



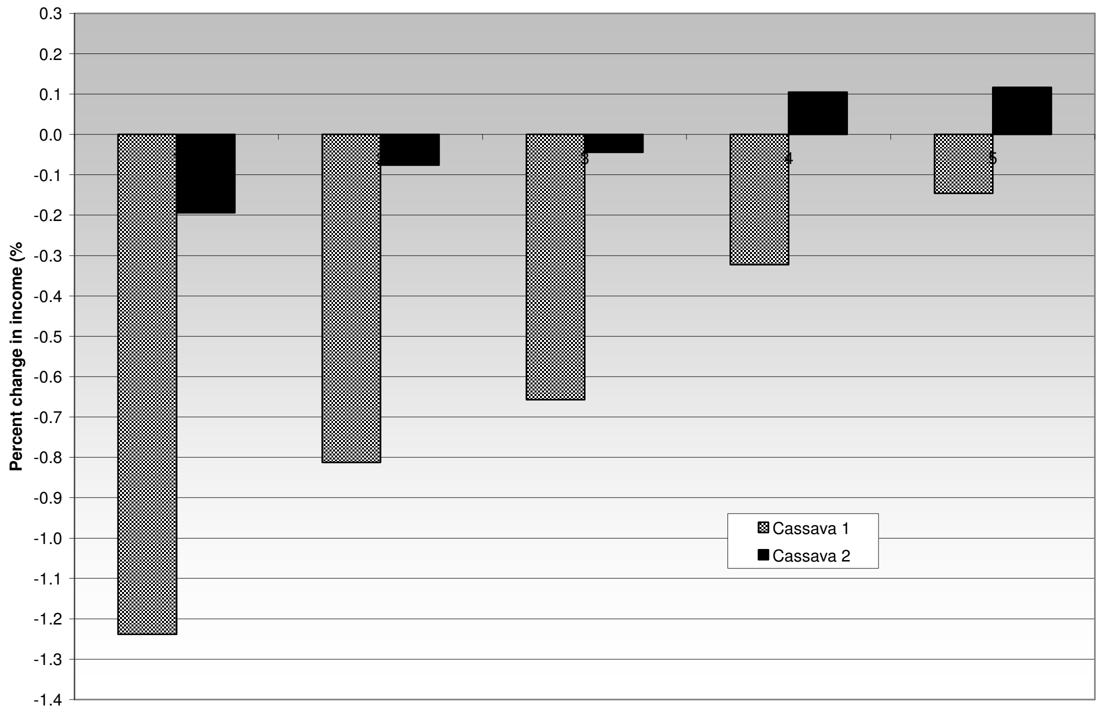

Source: Calculations by the author based on the ENAHO dataset for 2006.

**Figure 4: Sensitivity analysis for Case 1 (Potato 1) and Case 2 (Potato 2) household level welfare impacts in the case of potato in Peru for the rural sub sample**



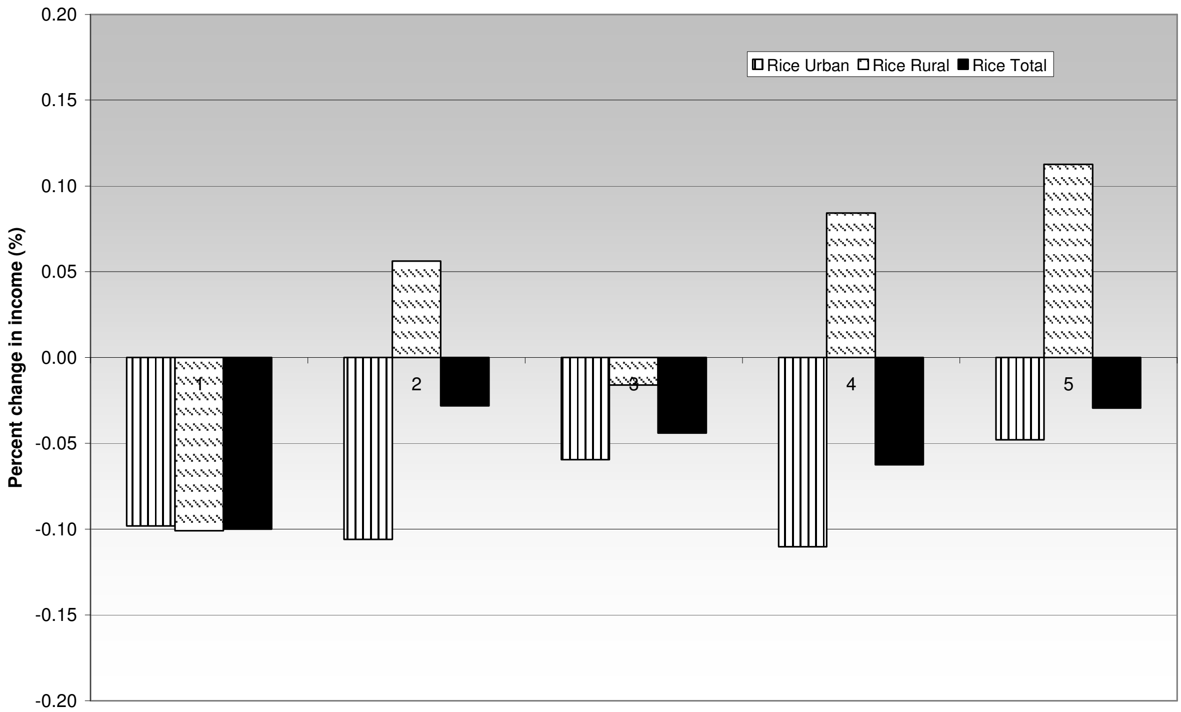

Source: Calculations by the author based on the ENAHO dataset for 2006.

**Figure 5: Sensitivity analysis for Case 1 (Cassava 1) and Case 2 (Cassava 2) household level welfare impacts in the case of Cassava for rural household in the Ruvuma region of Tanzania.**



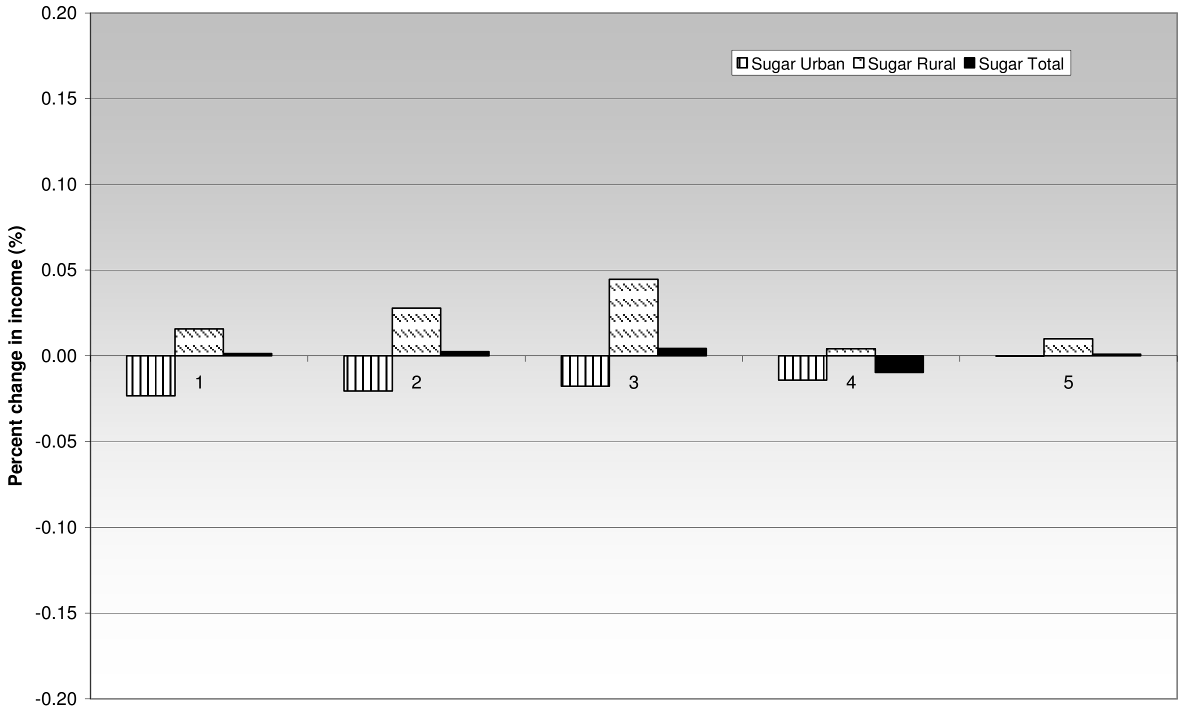

Source: Calculations by the author based on the Ruvuma Kilimanjaro FAO/WB/REPOA dataset of 2003/2004.

**Figure 6: Welfare impacts for a 10 percent increase in the producer price of rice.**



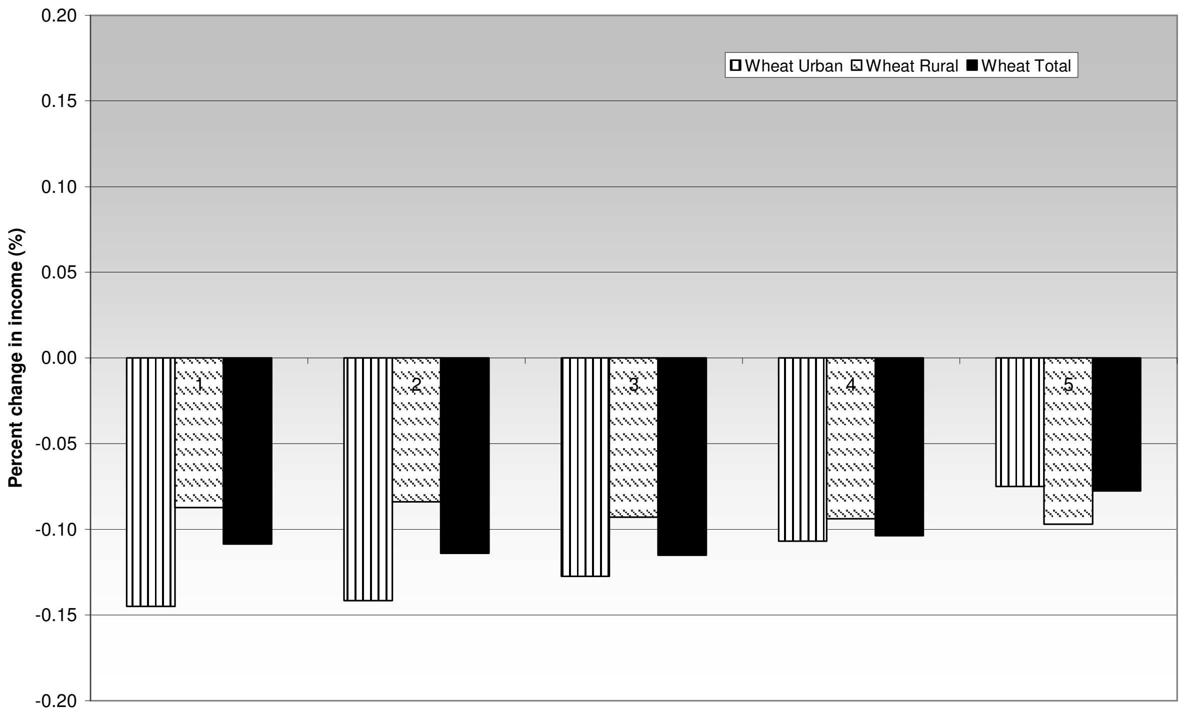

Source: Calculations by the author based on the ENAHO dataset for 2006.

**Figure 7: Welfare impacts for a 10 percent increase in the producer price of sugar.**



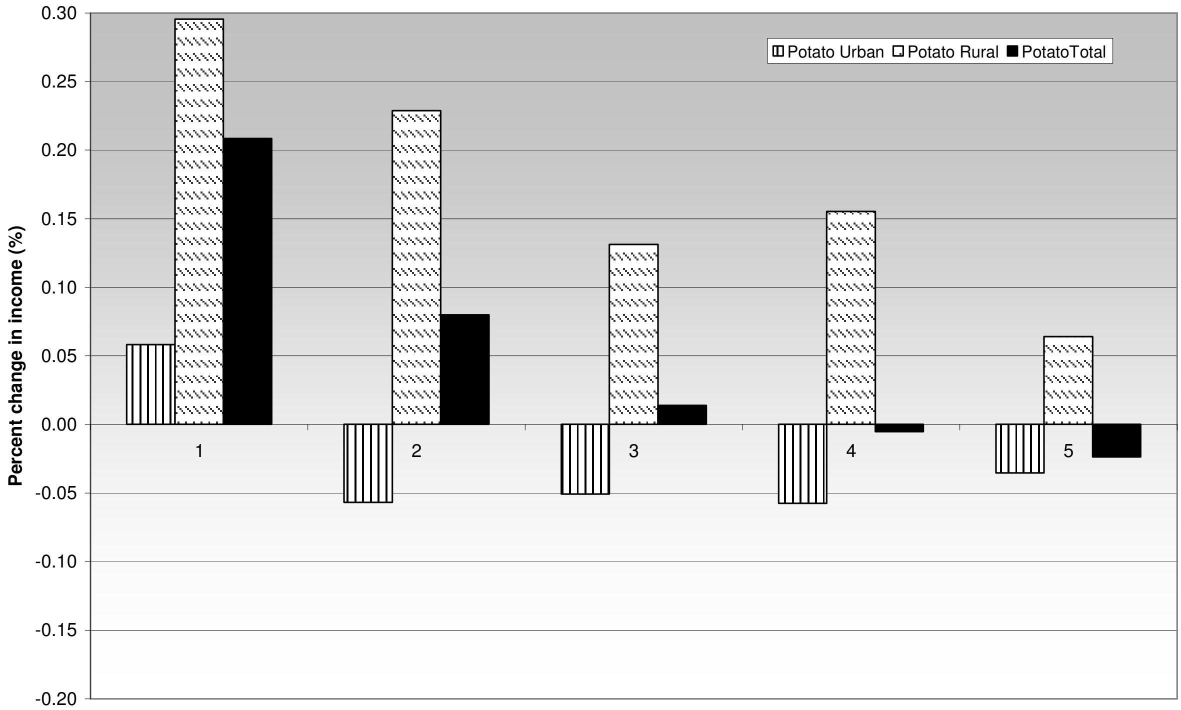

Source: Calculations by the author based on the ENAHO dataset for 2006.

**Figure 8: Welfare impacts for a 10 percent increase in the producer price of wheat.**



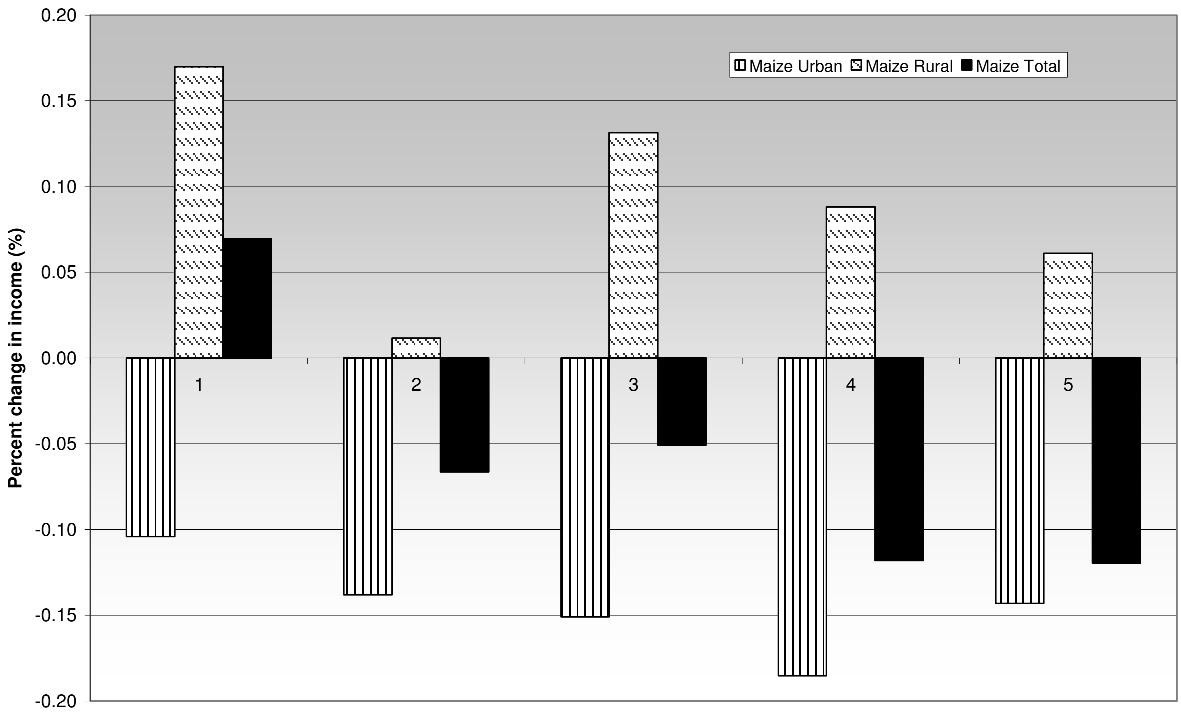

Source: Calculations by the author based on the ENAHO dataset for 2006.

**Figure 9: Welfare impacts for a 10 percent increase in the producer price of potato.**




Source: Calculations by the author based on the ENAHO dataset for 2006.

**Figure 10: Welfare impacts for a 10 percent increase in the producer price of maize.**




Source: Calculations by the author based on the ENAHO dataset for 2006.

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# Simulating exogenous and endogenous technology when depletables, renewables and pollution co-exist: how to achieve sustainability?

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**Abstract**
In the attempt to mitigate climate change and the severe consequences of fossil fuel pollution, a number of different energy options and strategies are available to policy makers today. We construct a model accounting for pollution damages and the option to use a depletable and a renewable energy resource in production. We investigate whether this economy can optimally achieve weak and strong sustainability under different technology options and production and consumption functional forms. We start by setting up an economy including for pollution and the key distinguishing factors between depletable and renewable resources. A benchmark case is constructed against which the introduction of technology and the variation in key parameters is assessed. Endogenous technology is modelled as learning by doing in the renewable resource. Results under all options are presented and some energy policy conclusions are put forward. It will be key not to solely rely on changes in the energy mix but to move to an economy that can substitute renewable energy resources for fossil fuels.

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**List of variables**

| | |
|---|---|
| C | Consumption |
| Z | Non-renewble |
| R | Renewable |
| F(.) | Production |
| E(.) | Energy production function |
| $\alpha$ | Share of depletable resource in the energy production function |
| $\beta$ | Share of energy in the production function |
| K | Physical capital |
| $\delta$ | Depreciation rate |
| g | Renewable cost per unit |
| P | Stock of pollution |
| $\gamma$ | Absorption rate of the environment |
| m | Exogenous technical progress |
| $\omega$ | Rate of exogenous technical progress |
| M | Stock of human capital |
| $\phi$ | Productivity of learning by doing |
| | |
| CD | Cobb Douglas |
| CES | Constant Elasticity of Substitution |

**Introduction**

Today, as the world energy demand increases and pollution impacts grow, the key environmental concern is understanding climate change, mitigating its harmful effects and assessing how this can be done sustainably. As Nordhaus clearly puts it "Global warming poses a unique mix of problems that arise from the fact that global warming is a global public good, is likely to be costly to slow or prevent, has daunting scientific and economic uncertainties, and will cast a shadow over the globe for decades, perhaps even centuries, to come" (pg.11, Nordhaus, 2007). In this light, it will be crucial to diversify energy portfolios, in the effort to curb impacts of climate change. In fact, recent research suggests that the increase in greenhouse gas emissions following the increasing energy demand, is likely to cause major irreversible climatic changes and damages. Alternative energy options, including all forms of renewable energy such as wind energy and solar systems, exist and are needed energy substitutes for fossil fuel. These energy options offer low or zero emissions alternatives and have the potential to provide technological benefits (WEA 2004 and 2006, IEA 2006 and 2007). Many economists have tried to address the key question for environment, growth and sustainable development, namely whether economic growth can be compatible or reconciled with care for the environment, as discussed below. Thus, building on the existing literature, the concern in this paper is whether renewable energy resources can play a lead role in addressing climate change problems thus allowing economies to position themselves on a sustainable path.

Different modelling approaches have been proposed depending on the focus of the research at the time. Four components constitute the main building blocks of the models behind this research: utility, pollution, environment, and resources (depletable and non-depletable). Pollution has been modelled both as a flow and as a stock, but as clearly argued in Withagen (1995), it is necessary to include pollution as a stock to capture the negative externalities effect that this poses showing that these externalities can hamper optimal economic growth. In fact, initially utility was modelled as a function of consumption only but more recently authors have started introducing environmental quality, or lack of this, in the utility function (Withagen 1995, Pittel 2002). The literature on depletable resources and growth is extremely vast, stemming from the seminal papers of Hotelling (1931), Stiglitz (1974), Dasgupta and Heal (1974) to name but a few, in which technical progress is found to play a key role.

Few authors have introduced renewable resources and depletable energy resources into this framework at the same time. Tahvonen and Salo (2001) propose a historical perspective arguing that economies transition from renewable to non-renewable back to renewable energy forms. Our work differs from theirs, since we believe that renewable energy sources differ over time. For example wind mills of yesterday are not the wind turbines of today. Similarly for the case of solar energy that requires technological improvements embedded in the development of solar panel technology. Further, we look into the future and the potential for renewable energy development, while Tahvonen and Salo (2001) take a more historical perspective. Krautkramer (1995), although in a different setting, concludes that an economy may be able to prevent decline in consumption through the use of a backstop technology.

The issue of sustainable development and economic growth under 'green' constraints has been analyzed by a number of authors over the last decade. Aghion and Howitt (1998) find that innovation is a necessary but not sufficient condition to achieve sustainable development when environmental pollution and exhaustible resources are accounted for; however, conclusions on the adequate policy are not reached. Pezzey and Withagen (1998) conclude that if natural resources are exhaustible then consumption is single peaked, declining from some point in time onward. Smulders (2000) provides an overview of the different perspectives and finds that growth can be sustained indefinitely only if technological change is unbounded and if natural and man-made capital can be substitutes. In sum, technology and resource substitutability play a key role.

Under the first respect, we model technological innovation as Learning by Doing. Since the seminal paper by Arrow (1962) a considerable amount of authors have discussed the learning opportunities offered by new technologies. As time proceeds and a new technology is implemented we can learn to use it better, or in other words, knowledge accumulates which can make the resource more productive or reduce production costs (Romer 1986, Aghion and Howitt 1998). Many economists see an advantage in capturing the benefits from the learning path over time at the onset of production activities. New technologies such as renewable energies offer the potential for learning by doing benefits, although the policy side and implementation of this is debated (Isoard and Soria 2001 and Rivers and Jaccard 2006 and Kobos et al 2006, Rasmussen 2001).

Turning to resource substitutability, our starting point is the strand of literature focusing on substitutability between natural and physical capital (see Smulders, 2003 as a recent example). Here, in light of the debate, we focus on substitutability between depletable and renewable energy resources.

We build on a companion paper, which is also the previous chapter of this thesis and depart from it in several ways: based on the model constructed, we introduce endogenous technology; we release the assumptions made in the previous paper and let production and utility functional forms vary; finally, we explicitly test for the optimality of both strong and weak sustainability.

In the companion paper, we made three main assumptions that allowed to obtain a closed form solution: first of all, we assumed Cobb Douglas production for energy entailing that both the renewable and non-renewable resource are essential, secondly we analysed the case of exogenous technology and thirdly we restricted our attention to the objective of strong sustainability defined as non-increasing pollution (Pittel, 2002). Using these three assumptions allowed us to obtain a set of conditions under which an economy using both renewable and non-renewable resources would be strongly sustainable under a finite time horizon. Nevertheless we found that, as the planning horizon extended to infinity, the mere existence and availability of renewable energy resources would no longer be sufficient for the economy to be strongly sustainable.

In this paper, on the other hand, we move away from some of the restrictions posed by these three assumptions. Due to the complexity of the model it is not possible to obtain a closed form solution, therefore the analysis presented here is undertaken in GAMS[1]. The introduction of mathematical simulation allows us to add endogenous technology, to introduce Constant Elasticity of Substitution (CES) production, releasing the "essentiality condition"[2], to vary consumer preferences and to analyze both weak and strong sustainability. We use the definition of non-declining utility for weak sustainability and non-increasing pollution for strong sustainability. We model endogenous technology as learning by doing in the renewable energy. The learning by doing captures the idea that while a society produces it learns to carry out activities more efficiently. This does not occur due to direct R&D

[1] Nordhaus (2007) has been a pioneer in mathematically simulating the effects of climate change by using economic and mathematical modelling tools and analyzing the efficient and inefficient strategies toward mitigating climate change damages.
[2] It is standard practice in the existing literature (Stiglitz 1974 for example) to start analysis with a Cobb Douglas functional form. This functional form entails that all inputs are essential for production. In this paper we release this assumption and analyze the implications of this.

investment decisions but as a side product of a certain activity, leading to the accumulation of knowledge in the economy (Arrow, 1962). This seems plausible in this case since renewable energies are still relatively new in the economies of today, i.e. their contribution to current energy demand is small, and offer a lot of space for learning how to use them better.

The paper proceeds as follows. We start off by recalling the structure of the companion paper model and building a baseline scenario. This baseline scenario will represent the benchmark against which to assess all simulations. We then introduce exogenous technology and simulate changes in the key parameters as identified in the companion paper. In addition to the companion paper here we look at implications for both weak and strong sustainability. We then add endogenous technology modelled as learning by doing in the renewable resource. Subsequently we release the assumption of the renewable and non-renewable energy resources being essential in energy production and introduce CES production. In the final set of simulations we generalize consumer preferences functional form. Conclusions are then drawn.

**The model with no technological progress**

The model in this paper builds on the structure and results obtained in the previous chapter of this thesis, including for a renewable and non-renewable energy resource and accounting for the effects on the environment. We set up an economy that can use both a renewable, R(t), and non-renewable energy resource, Z(t). Some key features differentiate these resources. The depletable energy resource is exhaustible and pollutes but costs less. On the other hand the renewable energy resource is not limited, does not pollute, offers learning by doing technological advantages but is more costly. Production is a function of physical capital, the renewable resource and non-renewable resource. Initially we model production in Cobb-Douglas form, for which both the renewable and non-renewable resource are essential, namely

$$F[K(t),R(t),Z(t)] = K(t)^{(1-\alpha)} EN(t)^{\alpha} = K(t)^{(1-\alpha)}[Z(t)^{\beta} R(t)^{(1-\beta)}]^{\alpha} \qquad (1)$$

The assumption of Cobb Douglas production will be released in the endogenous part of the analysis allowing us to move away from the essentiality condition embedded in Cobb Douglas specification for which $F(0,Z,R) = F(K,0,0) = 0$.

Pollution accumulates over time due to the use of the non-renewable resource in production, although partly re-absorbed naturally by the environment (see social planner's problem below). At the same time, pollution causes disutility to consumers. Therefore utility is a function of consumption and pollution, whereby individuals derive utility from consumption and are negatively affected by pollution[3], namely

$$u(C(t),P(t)) = \ln C(t) + \ln(\overline{P} - P(t)) \qquad (2)$$

[3] Standard conditions on the utility function hold, namely $U_C > 0$ and $U_P < 0$ and concavity of the utility function, i.e. , $U_{CC} < 0$ and $U_{PP} < 0$. The assumption of separability in the utility function entails that the level of pollution has no impact on $U_C$ and viceversa that consumption has no impact on $U_P$. Separability is a standard assumption (see for example Pittel (2002)).

where C(t) is consumption, P(t) is the pollution stock[4], and $\overline{P}$ is the uppermost pollution that society can withstand beyond which society would cease to exist[5].

A benevolent social planner maximizes utility subject to a pollution constraint, a depletable resource constraint and a capital accumulation constraint. Pollution accumulates based on the net amount of depletable resource used. The constraint on the depletable resource is the standard rule for decumulation of the stock of non-renewable resource. Physical capital accumulates based on output net of consumption, costs for the renewable resource and depreciation of physical capital. Structurally the problem is as follows:

$$\max_{\{C(t),R(t),Z(t)\}} \int_0^T u(C(t),P(t)) \cdot e^{-\rho t} dt \tag{3}$$

subject to

$$\dot{P}(t) = Z(t) - \gamma P(t) \tag{4}$$

$$\dot{S}(t) = -Z(t) \tag{5}$$

$$\dot{K}(t) = F[K(t),R(t),Z(t)] - C(t) - gR(t) - \delta K(t) \tag{6}$$

This is the structural form of the base case scenario which does not include for any technical progress. We will introduce exogenous and endogenous technical progress as we proceed in the analysis.

**The baseline simulation[6]**

Starting from the base model outlined above, we simulate an economy that is neither weakly nor strongly sustainable, which will represent the counterfactual for our set of

[4] As outlined in the introduction, we consider pollution to be a stock since we refer to fossil fuels and the disutility generated through the consequent accumulation of carbon dioxide pollution. This is inline with the discussion in Withagen (1995)
[5] We assume that this threshold level of pollution can never be reached using all existing non-renewable resources in one same point in time.
[6] Details of the GAMS programmes are contained in the appendices.

simulation. This means that as time progresses and the economy grows, the stock of pollution increases over time, while utility decreases (Figure 1).

The share of renewable energy in the economy plays a key role in the whole analysis and will be one of the key parameters under investigation. Currently, renewable energy contributes approximately 6 percent to total energy supply worldwide[7]. Due to this we start by setting the share of non-renewable energy, beta, at 0.94. This will represent the value of beta for the base case scenario. We test two additional values of beta, 0.8 and 0.7. As beta decreases, the role of renewable energy in the energy production is increasing. Figure 1 illustrates how, also for these two values of beta, the economy is still unsustainable, both in a weak and in a strong sense.

After having set up the base scenario, we let technology, production and consumption functions and key variables vary at different stages of the analysis and assess the impact of these on sustainable development. We start off by adding exogenous technological progress and then move to endogenous technological progress. In the case of endogenous technology, as the analysis proceeds, we add CES energy production and introduce a more general isoelastic utility function[8].

**The exogenous simulation set with exogenous technical progress**

Following the detailed analysis and conclusions obtained in the previous chapter of this dissertation, we introduce exogenous technical progress as resource augmenting technical progress following, among others, Stiglitz (1974) and Valente (2005) whereby technical progress is driven exogenously and formally described as $m(t) = e^{\omega t}$. Accordingly, the production function in this case will be the following:

$$F[K(t), m(t) \cdot R(t), Z(t)] = K(t)^{(1-\alpha)} EN(t)^{\alpha} = K(t)^{(1-\alpha)} [Z(t)^{\beta} (m(t)R(t))^{(1-\beta)}]^{\alpha} \qquad (7)$$

[7] This is the share of renewables in energy consumption in the EU-25 today based on the European Environment-State and Outlook 2005 report of the EU. This share encompasses all renewables. The target rate for 2030 is that this share increases to 20 percent, equivalent to a beta of 0.8 in the analysis presented here. Worldwide the current share of renewable energy is 0.5 percent, projected to increase under a business as usual scenario to 1.7 percent by 2030 (IEA 2006).

[8] In the current setting we are using a specific isoelastic function for utility, where the intertemporal elasticity of substitution is equal to 1.

We previously found that the rate of growth of the economy with exogenous technological progress was a function of the share of renewable resource, β, the share of the non-renewable resource, (1−β), and the rate of exogenous technological progress, ω, formally

$$\frac{\dot{Y}}{Y}^{EXO} = \frac{(1-\beta)}{\beta}\omega \qquad (8)$$

We now run two sets of simulations. In the first set we vary the rate of technical progress. In the second set, we define a minimum and maximum rate of technical progress, and let the share of the renewable resources in the economy vary.

We start by setting the rate of exogenous technical progress at a very low level and then gradually increase it. We initially set ω at 0.1 and then increase it up to 0.5 and 0.9. Results are reported in Figure 2. We find that increasing the rate of technical progress has no significant effect on the optimal pollution trajectory over time. On the other hand, when technical progress is comparatively fast, in the long run utility increases. Thus faster exogenous technical progress, at low levels of renewable resource market share, does not allow to achieve strong sustainability, but can lead to weak sustainability in the long run.

The second set of simulations adds changes in the resource share to changes in the rate of technological progress, see Figures 3 and 4. We select two cases, one of relatively slow and one of relatively rapid technical progress, namely by setting ω=0.1 and ω=0.9. We start from the base case share of non-renewable resource, 0.94, in which renewables hold a small share of the market, and decrease it to 0.8 and 0.7, allowing for a more prominent role of the renewable energy resource.

We find that in all cases the economy is not strongly sustainable and that pollution always increases over time. For low levels of technological progress, as the share of the renewables increases, the level of pollution decreases, but when technological progress is fast, the contrary is true. This is because beta plays a double role, on the one hand as beta decreases the share of renewable resources increases, on the other, a decline in beta also coincides with an increase in the rate of technical progress which in turns makes all resources more productive. When the rate of technological progress is fast enough, it seems that the second effect overcomes the first, so that overall more pollution is optimal for the economy. For what concerns utility, the economy manages to reach a weakly sustainable path when technological progress is fast and the share of the depletable resource decreases. These results are in line with the conclusion achieved in the companion paper and summed up above. Weak sustainability is possible because of the exponential growth rate of technical progress that generates rapid output and consumption growth, counteracting the negative effects of increasing pollution stock in terms of utility. On the other hand, as shown in the companion paper, strong sustainability cannot be achieved.

**The endogenous simulation set with learning by doing in the renewable resource**

We introduce endogenous technical progress in the form of learning by doing. The idea here is that as time proceeds and the renewable energy source is used, society learns to use this resource better. Through the use of the renewable resource a knowledge base accumulates. The rate of accumulation of knowledge is directly proportional to the amount of renewable resource used. As time proceeds and knowledge accumulates, the renewable input in energy production becomes more productive. Formally, the evolution of knowledge, M(t), over time is defined as

$$\dot{M}(t) = \varphi M(t) R(t) \tag{9}$$

or in other words the rate of knowledge accumulation is proportional to the amount of renewable energy source used in society

$$\frac{\dot{M}(t)}{M(t)} = \varphi R(t) \tag{9'}$$

where $\varphi$ represents a productivity parameter. The question we investigate now is whether the knowledge accumulation process directly linked to the use of the renewable energy resource, captured in (9) or (9'), can contribute toward achieving both weak and strong sustainability. More generally, what role does knowledge accumulation play in achieving sustainability?

The production function can be re-written as follows:

$$F(K(t), M(t)R(t), Z(t)) = [Z(t)^{\alpha} (M(t)R(t))^{\beta} K(t)^{1-\alpha-\beta}] \tag{10}$$

We add the knowledge constraint (9) to the previously shown social planner's problem , i.e. equations (3) to (6). In this case, the current value Hamiltonian is

$$H(t) = U(C(t), P(t)) + \lambda(t)[Z(t) - \gamma P(t)] + \xi(t)[-Z(t)] + \\ + \mu(t)\{F[K(t), (M(t)R(t)), Z(t)] - C(t) - gR(t) - \delta K(t)\} + \omega(t)[\varphi M(t)R(t)] \quad (11)$$

The first order conditions with respect to consumption, the amount of depletable resource extracted and the renewable resource, namely the control variables, are:

$$\partial H / \partial C = 0 \Rightarrow 1/C = \mu \quad (12)$$

$$\partial H / \partial Z = 0 \Rightarrow \mu F_z = \xi - \lambda \quad (13)$$

$$\partial H / \partial R = 0 \Rightarrow \mu F_R + \omega \phi M = \mu g \quad (14)$$

Specifically, while (12) is standard, condition (13) requires that the marginal benefits from depletable resource use equal marginal social costs. Further, condition (14) implies that marginal costs of renewable resources must be equal to marginal social benefits, given by the sum of marginal benefits in production *plus* marginal LBD benefits.

The costate equations for the state variables, namely pollution, the stock of depletable resource, physical capital and knowledge are as follows

$$\dot{\lambda} = (\rho - \gamma)\lambda - u_P(\cdot) \quad (15)$$

$$\dot{\xi} = \rho \xi \quad (16)$$

$$\dot{\mu} = \mu[\rho + \delta - F_K] \quad (17)$$

$$\dot{\omega} = (\rho - \varphi R)\omega - \mu F_M \quad (18)$$

And the following set of transversality conditions on the state variables need to hold for optimality to be met

$$e^{-\rho T}\lambda(T)P(T)=0 \qquad (19)$$

$$e^{-\rho T}\xi(T)S(T)=0 \qquad (20)$$

$$e^{-\rho T}\mu(T)K(T)=0 \qquad (21)$$

$$e^{-\rho T}\omega(T)H(T)=0 \qquad (22)$$

We now start to test whether the introduction of endogenous technology can lead to weak and strong sustainability. To this aim we set up a number of simulations. Initially we run a sensitivity analysis of the model to the initial level of knowledge in the economy and to the productivity of the knowledge sector. We call this set of simulations Set 1. Secondly, we substitute Cobb Douglas energy production with a CES energy production function. This allows us to move away from the assumption that both the renewable and depletable resource are essential in energy production. We test for varying levels of substitutability between the two resources. To this end, we investigate the sensitivity of the model to varying levels of the elasticity of substitution between the renewable and non-renewable energy source. We also vary the share of the renewable resource in the economy and combine this with a CES energy production function. These two sets of simulations are Set 2 and Set 3. In the final set of simulations, Set 4, we remove the assumption of unit intertemporal elasticity of substitution to evaluate how such assumption affects our results and include a wider range of consumers' preferences.

**Endogenous simulation set with Cobb Douglas energy production (Set 1).**

In an economy that can benefit from knowledge accumulation via the use of the renewable resource, we assess whether the productivity of the knowledge sector and the initial knowledge base play a role in achieving weak and strong sustainability. We then add the share of the renewable resource to the analysis to understand how the size of the resource can contribute toward sustainability when learning by doing from the renewable resource is present.

As shown in Table 1, we run 12 simulations subdivided in groups of four. Each group of simulations has a constant level of beta. The first group of simulations, group 1, uses the base case scenario share of depletable resources, namely sets beta equal to 0.94. Group 2 if for beta equal to 0.8 and group 3 for beta equal to 0.7. For each level of beta, we test the cases of a relatively high and relatively low initial knowledge base, $M_0$. In the case of a low initial knowledge base we set $M_0$ equal to 10, for the high case we set $M_0$ equal to 100. We increase the productivity parameter from 0.5 to 0.9. Results for pollution and utility are shown in figures 5 and 6.

In the case of pollution, we find that the optimal pollution trajectory is always increasing, showing learning by doing in the renewable resource is not sufficient to guarantee strong sustainability. Further, at higher levels of the initial knowledge base and a more productive knowledge sector, the pollution path continues to be increasing. When the resource share is added to the analysis, the optimal level of pollution is lower compared to the other cases, but still increasing. Thus, when both the renewable and depletable resource are essential in energy production, the mere existence of the resource and the technology benefits from learning to use the resource better, are no guarantee that an economy will be able to lower its emissions and move to a strongly sustainable path.

Introducing learning by doing does not lead to an optimally weakly sustainable path either. We find that for the base case of beta equal to 0.94, the initial knowledge base and the sector productivity, have no impact on the optimal path of utility. As the share of the deplatable resource decreases, the initial knowledge base and the sector productivity play a larger role.

**Endogenous simulation set with CES energy production (Set 2 and Set 3).**

We now release the crucial assumption of essentiality of both resources in energy production by introducing CES energy production. This type of production entails that the two resources can be substituted one for another at a varying rate. The extreme case, when the elasticity of substitution, sigma, is equal to 1, entails that Z and R can be fully substituted one for another.

$$F[K(t), m(t) \cdot R(t), Z(t)] = K(t)^{(1-\alpha)} EN(t)^{\alpha}$$

and where $EN(t) = \left[\beta Z(t)^{\sigma} + (1-\beta) R(t)^{\sigma}\right]^{1/\sigma}$

or in other terms $F[K(t), m(t) \cdot R(t), Z(t)] = K(t)^{(1-\alpha)} \left\{\left[\beta Z(t)^{\sigma} + (1-\beta) R(t)^{\sigma}\right]^{1/\sigma}\right\}^{\alpha}$ (23)

Sigma can vary from 1 to $-\infty$. For sigma=1 the resources are perfect substitute. Sigma=0 is a limit case when the CES production function tends to the Cobb Douglas function (this case has been analyzed above). As sigma moves toward $-\infty$, R and Z become less and less substitutable, complements in the limit. As listed in Table 2, we run 5 simulations setting the elasticity of substitution between R and Z, called sigma, equal to -3, -1, -0.5, 0.5. We use base values for the knowledge base and the productivity of the knowledge sector, respectively setting these at 10 and 0.5. The share of non-renewables in energy production is 0.94.

We find that substitutability between the inputs in energy production plays a key role in reducing pollution and achieving strong sustainability, as shown in Figure 7. When the depletable and renewable resource are not substitutable pollution increases. This holds true for all values tested with the exception of the perfect substitutability case. It is only when the two energy inputs are perfectly substitutable that the optimal path of pollution steadily declines over time leading to a strongly sustainable path for which pollution levels are also significantly lower.

The case of utility is somewhat different, see Figure 8. When resources are not substitutable, utility levels decline over time. In the case of perfect substitutability, utility initially increases but declines in the long run. Overall weak sustainability is not achieved in the long run in any case.

We now add the share of the renewable resource to the analysis, simulation Set 3 as shown in Table 3. We find a set of paths consistent with the results above. The share of the renewable resource plays no major role in modifying the pollution and utility paths, Figures 9 and 10. Strong sustainability is achieved when resources are perfectly substitutable and the resource share does not modify the path significantly. In the case of utility, when resources are not substitutable, utility declines. In the case of perfect substitutability, utility initially increases but declines in the long run. As the depletable resource share decreases, utility levels rise and increase for a longer period of time, but still decrease in the long run. This result is in line with the existing literature (see Pezzey and Withagen, 1998), although here a renewable resource and learning by doing have been added.

These results for utility and consequently weak sustainability are puzzling since we obtain strong but not weak sustainability. In order to shed some light on this puzzle, we do two things. First, we check if the value of the objective function, namely the Net Present

Value (NPV) of total flow of utility over time, increases as knowledge accumulation becomes more productive and the share of the renewable resource increases. We plot the value of NPV as a function of sigma and for two values of beta. We find that, as shown in Figure 11, increasing the substitutability between the resources increases the total value of the objective function. Furthermore, given the rate of substitution, higher shares of renewables also lead to higher values of the NPV. Therefore, although we still do not obtain weak sustainability, we find that for society overall increasing the energy mix and the substitutability among resources is positive. As a second step, Figure 12, we also drastically increase the productivity factor of the knowledge sector. In this case we find that in the very long run, utility increases for high enough levels of sigma. Nevertheless these results are still not conclusive on the utility side.

**Endogenous simulation set with general isoelastic utility (Set 4).**

Since we find that no other key parameters lead to steadily increasing utility over time, we now generalize consumer preferences by allowing the elasticity of substitution to vary, as discussed in Romer (2001) and Smulders (2000). We keep, however, the separability assumption. The Constant Relative Risk Aversion (CRRA) utility function is defined as follows:

$$u(C(t),P(t)) = \frac{C(t)^{1-\tau}}{1-\tau} + \frac{(\overline{P} - P(t))^{1-\tau}}{1-\tau} \tag{24}$$

where $\tau$ represents the household's willingness to shift consumption between different time periods. The smaller $\tau$, the more willing the household is to allow its consumption to vary over time or in the words of Smulders, the more *flexible* the consumer. The intertemporal elasticity of substitution is defined as $1/\tau$ so as $\tau$ decreases the intertemporal elasticity of substitution increases showing how consumers become more willing to substitute consumption across time periods. It can be shown that when $\tau$ tends to 1 this functional form converges to the logarithmic functional form, namely, the functional form in (22) is a generalization of the previous preference function in (2).

Building on the conclusions from the previous set of simulations, we start from the case for which we had obtained an optimal strongly sustainable path, featuring a depletable resource share of 0.94, high productivity in the knowledge sector and perfect substitutability between the depletable and renewable resource.

We test two cases, one case in which consumers are relatively more flexible compared to the previous case and one in which consumers are comparatively less flexible. As discussed, in the limit logarithmic case used previously to describe consumer preferences, $\tau$ was equal to 1. Therefore we set $\tau$ equal to 0.9, the case of a relatively more flexible consumer, and 1.1, the case of a relatively less flexible consumer.

We plot the optimal utility path under the two cases, Figure 13. We find that when consumers are less flexible, utility declines over time. In the case of a more flexible consumer, utility increases in the long run. Therefore, flexibility of the consumer, ie the willingness of the consumer to substitute consumption across time periods, is important in reaching a weakly sustainable path.

Taking the case of a more flexible consumer, ie $\tau$ =0.9, as a second step we vary the productivity parameter and the share of the renewable resource, Figure 14. We find that the productivity of the knowledge sector is key for weak sustainability, once a more flexible consumer is introduced. A long run weakly sustainable path is obtained when the productivity factor reaches 100. The share of the renewable resource contributes to this. When we decrease beta from 0.94 to 0.7, the utility path is more steadily increasing.

***Conclusions***

In an attempt to contribute to the debate on climate change and the role for renewable energy resources, this paper presents a model that brings together a number of the building blocks in recent environmental economic literature, including for pollution, renewable and depletable energy resources, and technological progress. The scope of the paper is to assess how and if renewable resources can play a key role in achieving weak and strong sustainability, respectively defined as non-declining utility and non-inceasing pollution stock.

In the model we set up, society can choose whether to use a renewable energy resource or a depletable one, differentiated based on their contribution to pollution, cost, technology and availability. Renewable resources offer learning by doing potential since society can learn to use them better through renewable resource-related knowledge accumulation.

The key aspects we analyze in the paper are the roles played by technological improvement, substitutability between the renewable and depletable resource in energy production, and consumer flexibility.

With regards to technological progress we analyze two cases: firstly exogenous technology modelled as resource augmenting technological progress and, secondly, endogenous technology in the form of learning by doing in the renewable resource. Once endogenous technology is introduced, in order to account for the full range of substitution possibilities, we release the assumption of Cobb Douglas production and introduce CES production. With respect to consumer preferences, we initially use a logartithmic utility function and then replace it with a more general CRRA utility function. Due to the structural complexity in the endogenous case, it is not possible to obtain a closed form solution so the whole problem is mathematically simulated in GAMS. We therefore start by building a benchmark case that is neither strongly nor weakly sustainable whereby utility is declining and pollution is increasing. The effects of exogenous technological improvement, endogenous learning by doing, key parameters and functional forms, are then assessed in reference to this baseline scenario.

In the exogenous technology case, we investigate the role of two key parameters, namely the rate of technological progress and the share of the renewable resource in energy production. We find that increasing the rate of technological progress alone does not allow to achieve strong and weak sustainability. In the long run though, technological progress does lead to increasing utility if fast enough. When the effect of increasing the share of energy generated from renewable resources is added, this result is clearer. Fast technical progress and larger dependence on renewable resources leads to a weakly sustainable path. Nevertheless, the result for strong sustainability remains unchanged. The optimal pollution path is constantly increasing, so over time more and more pollution accumulates.

In the endogenous case, when energy production is Cobb Douglas, neither strong nor weak sustainability are achieved. We find that relaxing the essentiality condition of the energy inputs plays a crucial role. In fact, a declining optimal pollution path is obtained only when CES energy production is introduced and the resources are perfectly substitutable. In this case though, results for utility are puzzling, we therefore initially refer to the net present value (NPV) for some indication of preference. Based on the NPV of the simulations, we confirm that increasing the share of the renewable resources increases the NPV. Furthermore, when coupled with sigma, we find that consumers prefer an economy in which R and Z can be perfectly substituted for one another and where R is used more heavily in energy production.

Due to the puzzling nature of the utility results, we then move to a more general utility functional form capable of including a wider range of consumer preferences. We find that only when consumers are more flexible, i.e. more willing to substitute consumption across time periods, will this type of economy with endogenous technology be weakly, and strongly, sustainable over time.

The main message from our analysis is twofold:

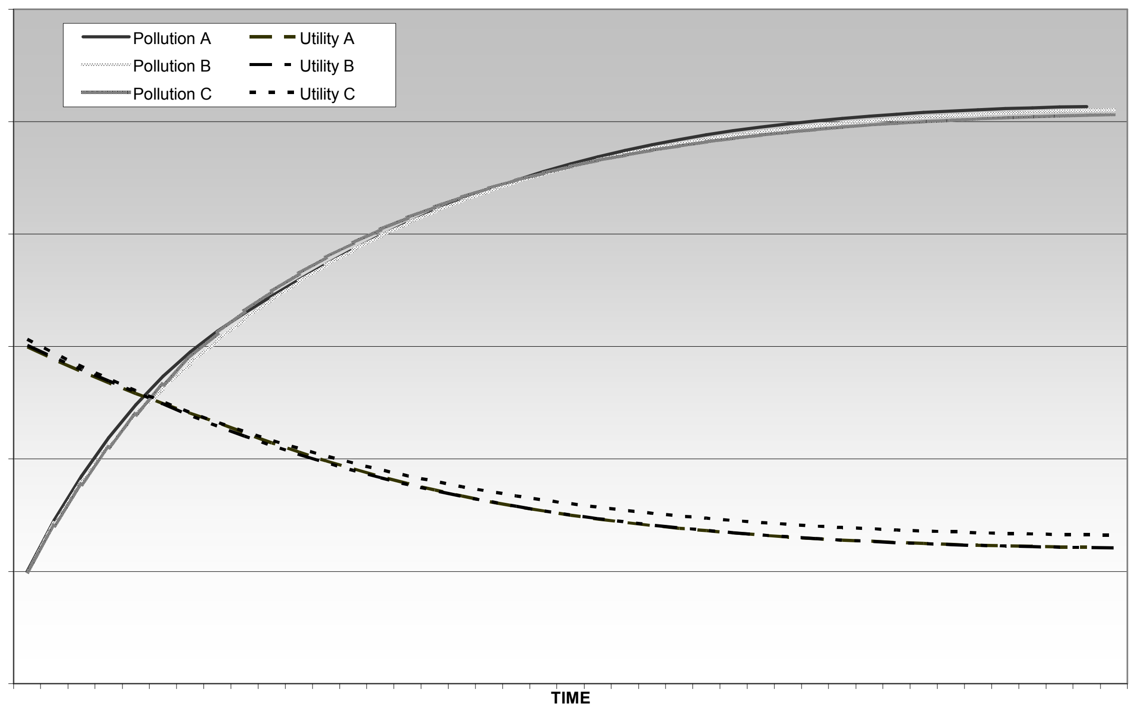
- a short run policy in terms of changes in the policy mix is indeed useful to take us on a more weakly sustainable path, if the role of renewables is sufficiently high. The level of pollution is, however, always increasing, so that we will be able to sustain such living standards only over a finite time span.
- Sustainable development in the long run, instead, requires a change in technology such that we can substitute between renewable and non renewable resources.

A strong political will is therefore needed. The change from a non renewable to a renewable energy system is indeed not an easy step but it is the only way to achieve strong sustainability in the long run. In fact, a change in the energy mix only moves doomsday a little forward.

Possible directions for further research are:

- Empirical analysis by applying this model to the case of a country's economy.
- Further investigate the way technical change and natural resources are modelled, for example by explicity adding the cost of the depletable resource, and/or by including a declining renewable resource cost function, resulting from technical progress.
- The inclusion of environmental policy in our setting which would imply solving a decentralized model and investigating optimal environmental policy in the presence of technical change.

**Figure 1: Base simulation model with no technology.**




Simulation A: Beta= 0.94; Simulation B: Beta= 0.80; Simulation C: Beta=0.70

**Figure 2: Variation in pollution and utility optimal paths upon increases in the exogenous growth rate of technological innovation, at constant beta.**

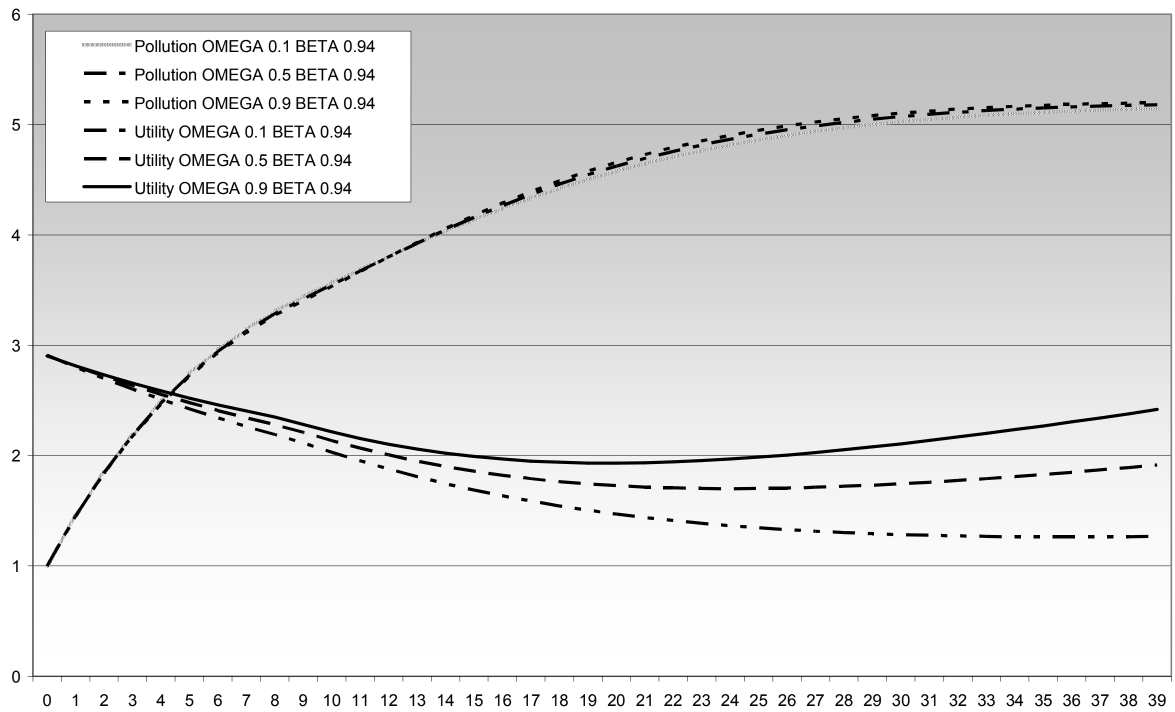


**Figure 3: Optimal pollution trajectory upon increases in the exogenous growth rate of technological innovation and varying beta.**

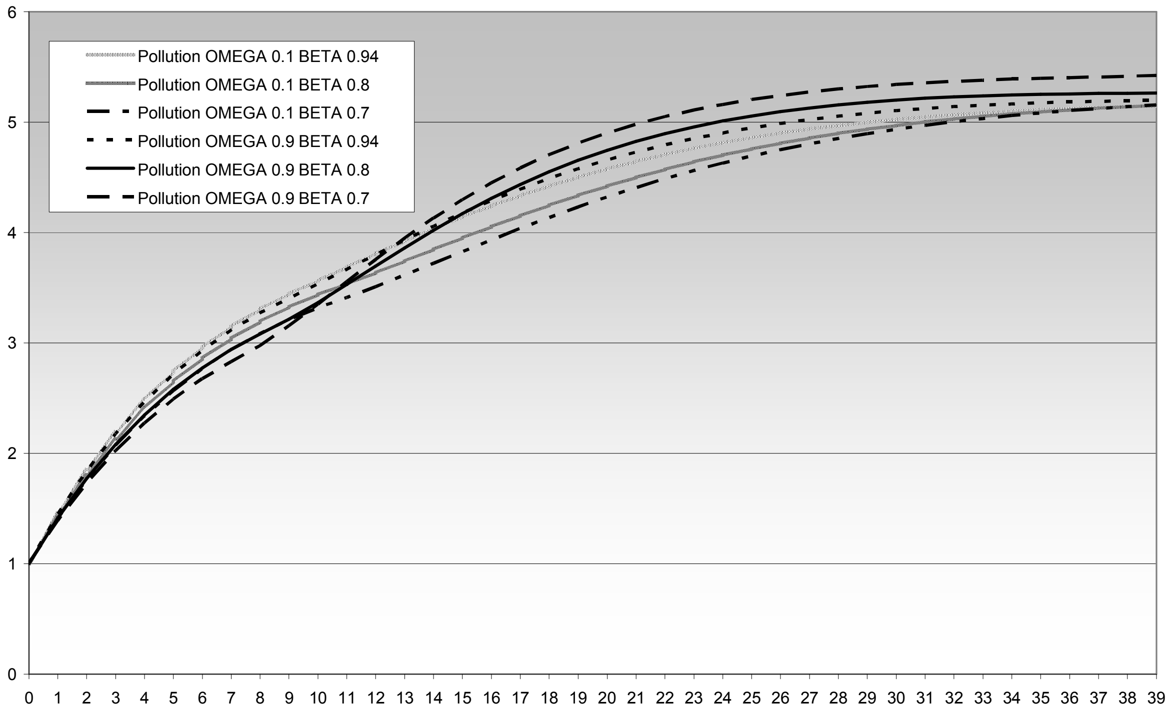



**Figure 4: Optima utility trajectory upon increases in the exogenous growth rate of technological innovation and varying beta.**

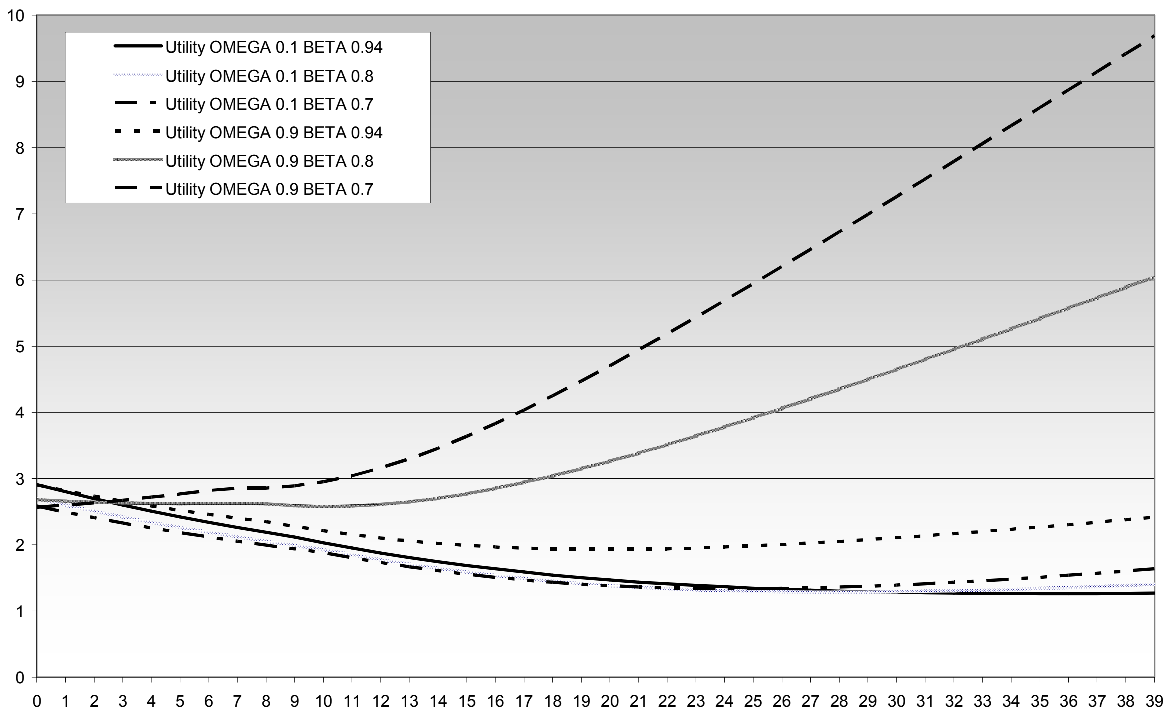


**Table 1: List of simulations in SET1**

| Simulation | Simulation Group | Production | Beta | Mo | Phi |
|---|---|---|---|---|---|
| A | 1 | CD | 0.94 | 10 | 0.5 |
| B | 1 | CD | 0.94 | 10 | 0.9 |
| C | 1 | CD | 0.94 | 100 | 0.5 |
| D | 1 | CD | 0.94 | 100 | 0.9 |
| E | 2 | CD | 0.8 | 10 | 0.5 |
| F | 2 | CD | 0.8 | 10 | 0.9 |
| G | 2 | CD | 0.8 | 100 | 0.5 |
| H | 2 | CD | 0.8 | 100 | 0.9 |
| I | 3 | CD | 0.7 | 10 | 0.5 |
| J | 3 | CD | 0.7 | 10 | 0.9 |
| K | 3 | CD | 0.7 | 100 | 0.5 |
| L | 3 | CD | 0.7 | 100 | 0.9 |

CD=Cobb Douglas, CES=Constant Elasticity of Substitution, Beta=Share of Depletable in the CD, Sigma=Elasticity of Substitution in CES, M0=Initial level of human capital, Phi=Productivity Factor,

**Figure 5: Pollution levels for Set 1 simulations in the endogenous technology case.**

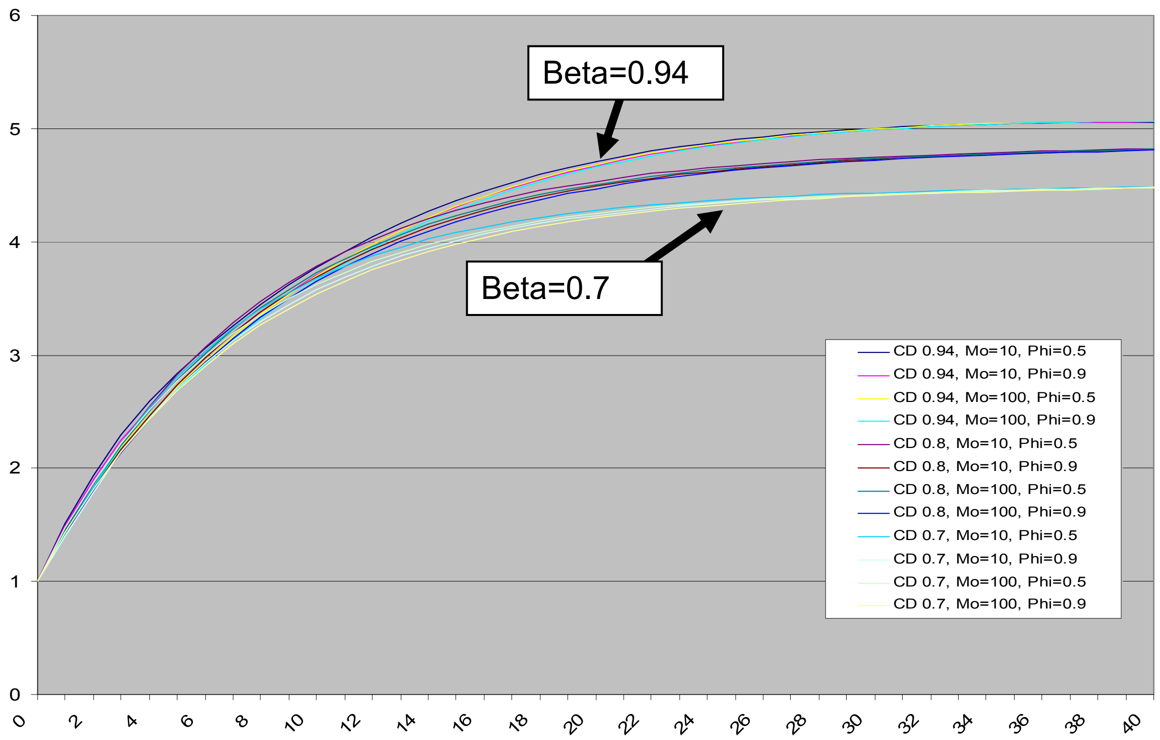


**Figure 6: Utility levels for Set 1 simulations in the endogenous technology case.**

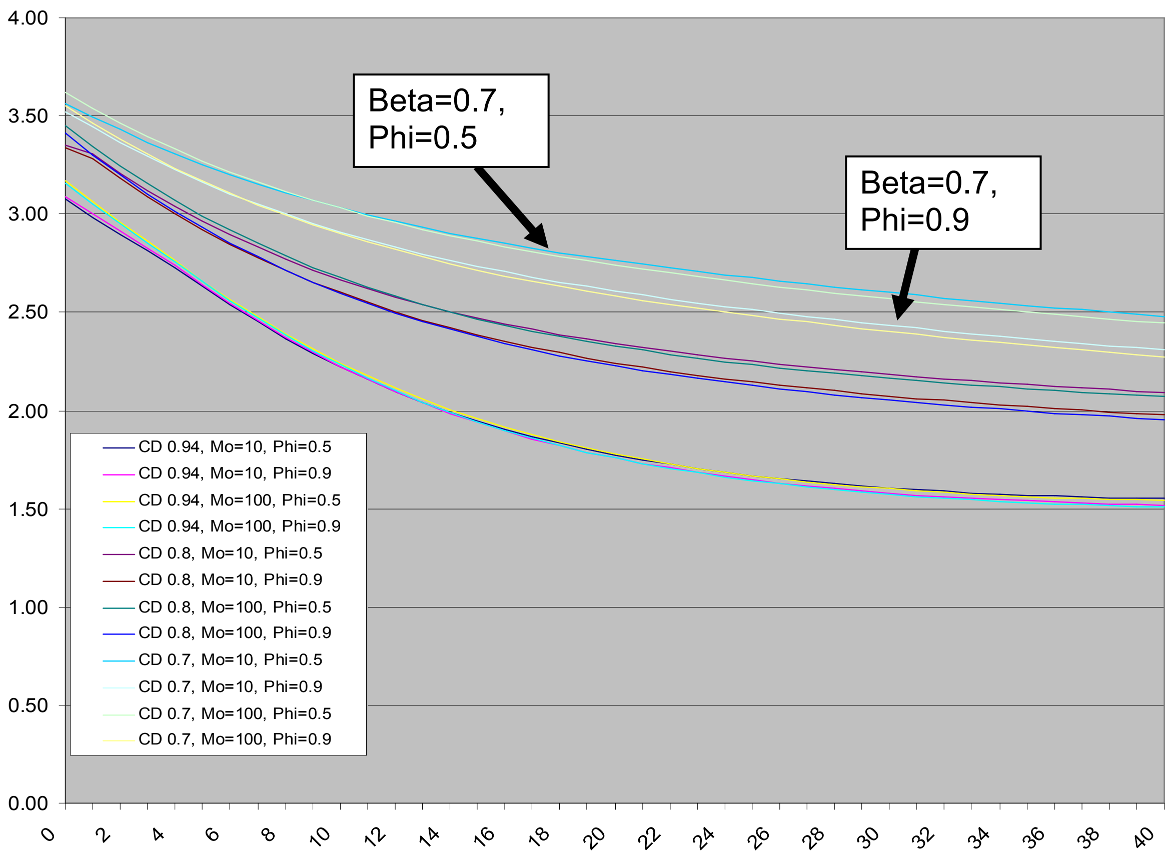



**Table 2: List of simulations in SET2**

| Simulation | Production | Beta | Sigma | Mo | Phi |
|---|---|---|---|---|---|
| A | CES | 0.94 | 1 | 10 | 0.5 |
| B | CES | 0.94 | 0.5 | 10 | 0.5 |
| C | CES | 0.94 | -0.5 | 10 | 0.5 |
| D | CES | 0.94 | -1 | 10 | 0.5 |
| E | CES | 0.94 | -3 | 10 | 0.5 |

CD=Cobb Douglas, CES=Constant Elasticity of Substitution, Beta=Share of Depletable in the CD, Sigma=Elasticity of Substitution in CES, M0=Initial level of human capital, Phi=Productivity Factor,

**Figure 7: Pollution levels for Set 2 simulations in the endogenous technology case.**

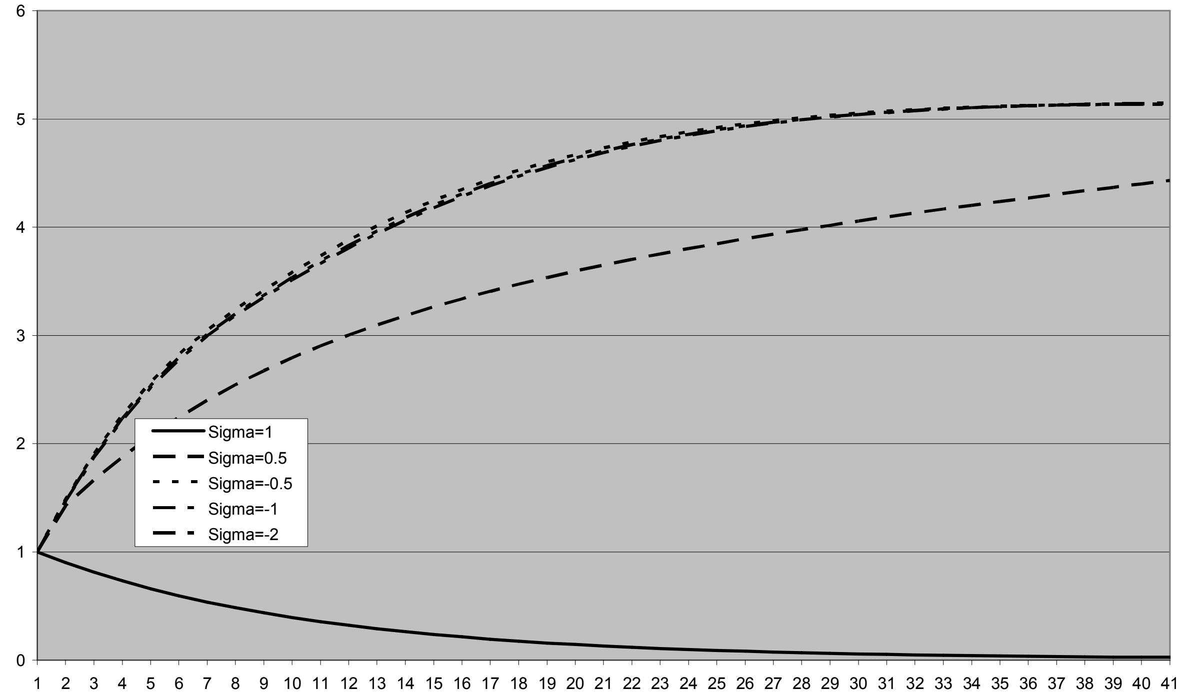



**Figure 8: Utility levels for Set 2 simulations in the endogenous technology case**

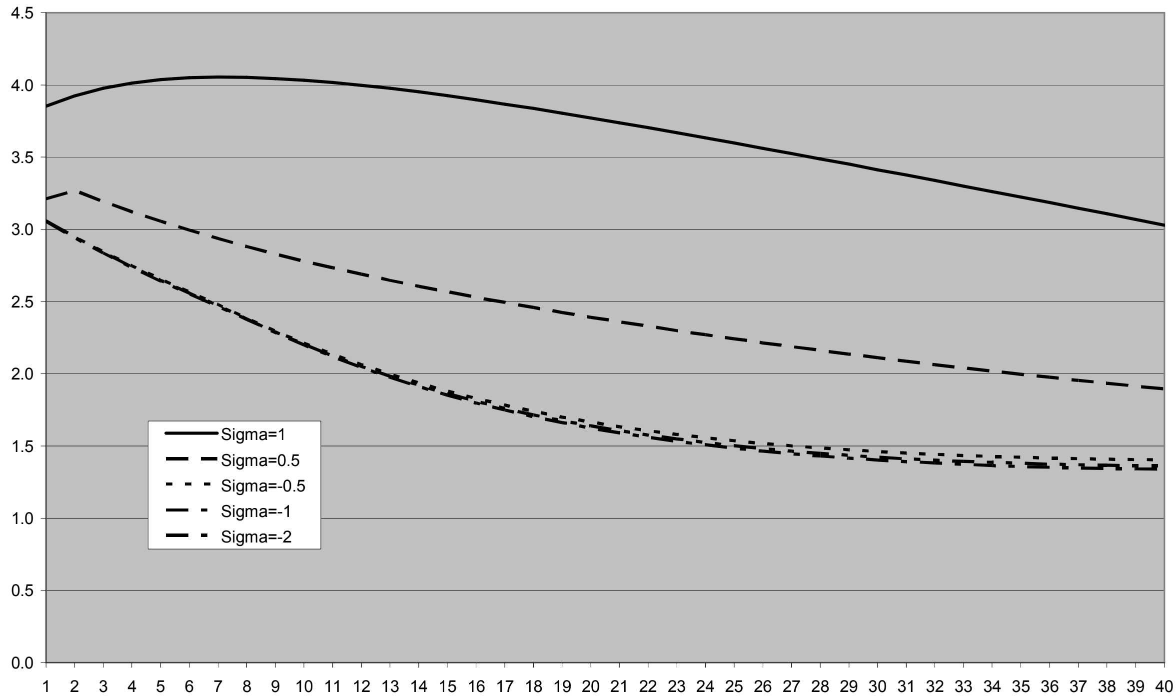


**Table 3: List of simulations in SET3**

| Simulation | Production | Beta | Sigma | Mo | Phi |
|---|---|---|---|---|---|
| A | CES | 0.94 | 1 | 10 | 0.5 |
| B | CES | 0.8 | 1 | 10 | 0.5 |
| C | CES | 0.7 | 1 | 10 | 0.5 |
| D | CES | 0.94 | -2 | 10 | 0.5 |
| E | CES | 0.7 | -2 | 10 | 0.5 |

CD=Cobb Douglas, CES=Constant Elasticity of Substitution, Beta=Share of Depletable in the CD, Sigma=Elasticity of Substitution in CES, M0=Initial level of human capital, Phi=Productivity Factor,

**Figure 9: Pollution levels for Set 3 simulations in the endogenous technology case.**

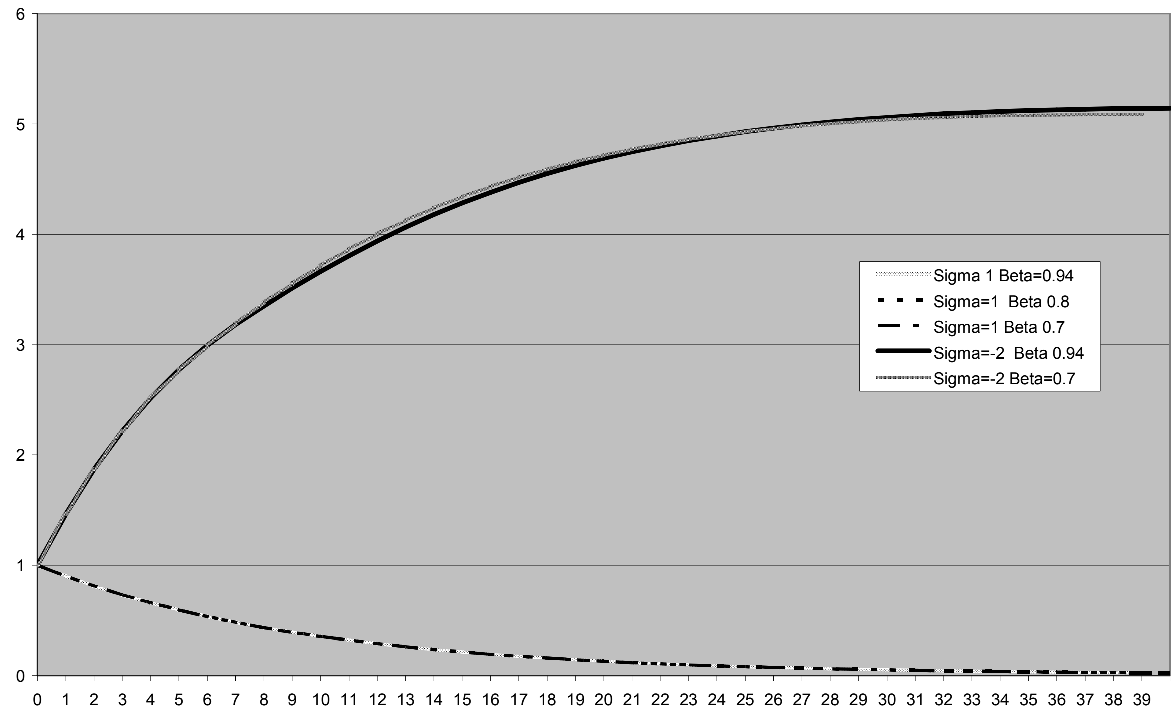


**Figure 10: Utility levels for Set 3 simulations in the endogenous technology case.**

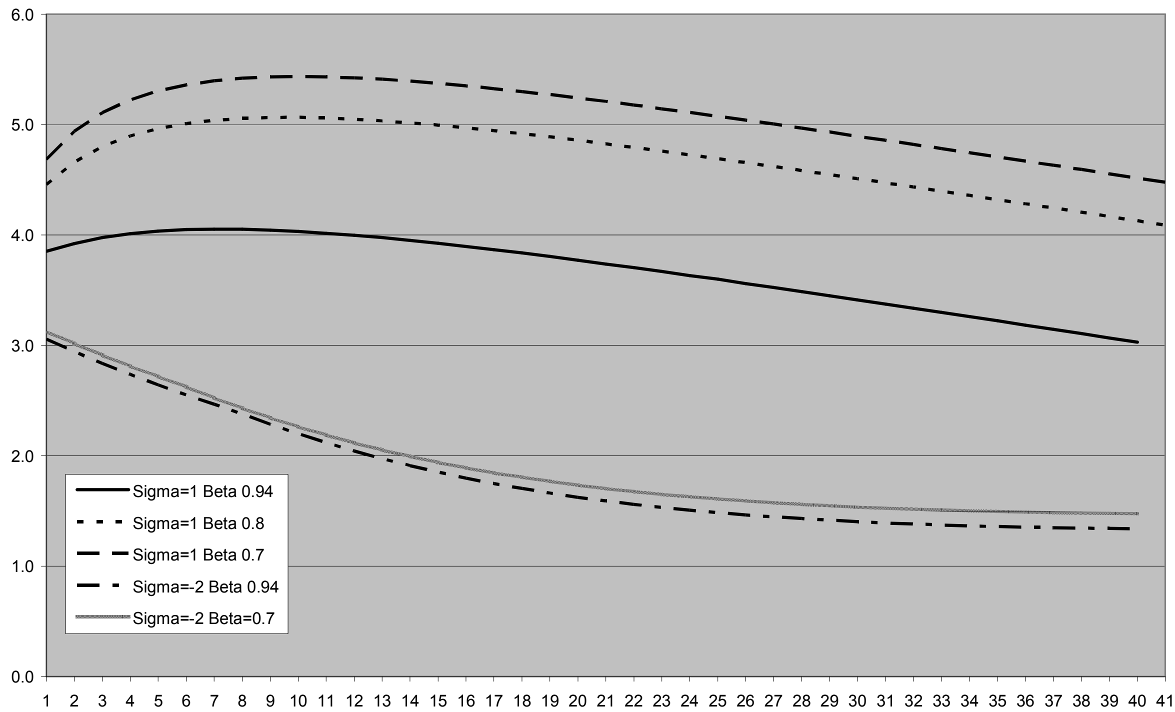



**Figure 11: Net present value at varying SIGMA and for decreasing depletable resource shares.**

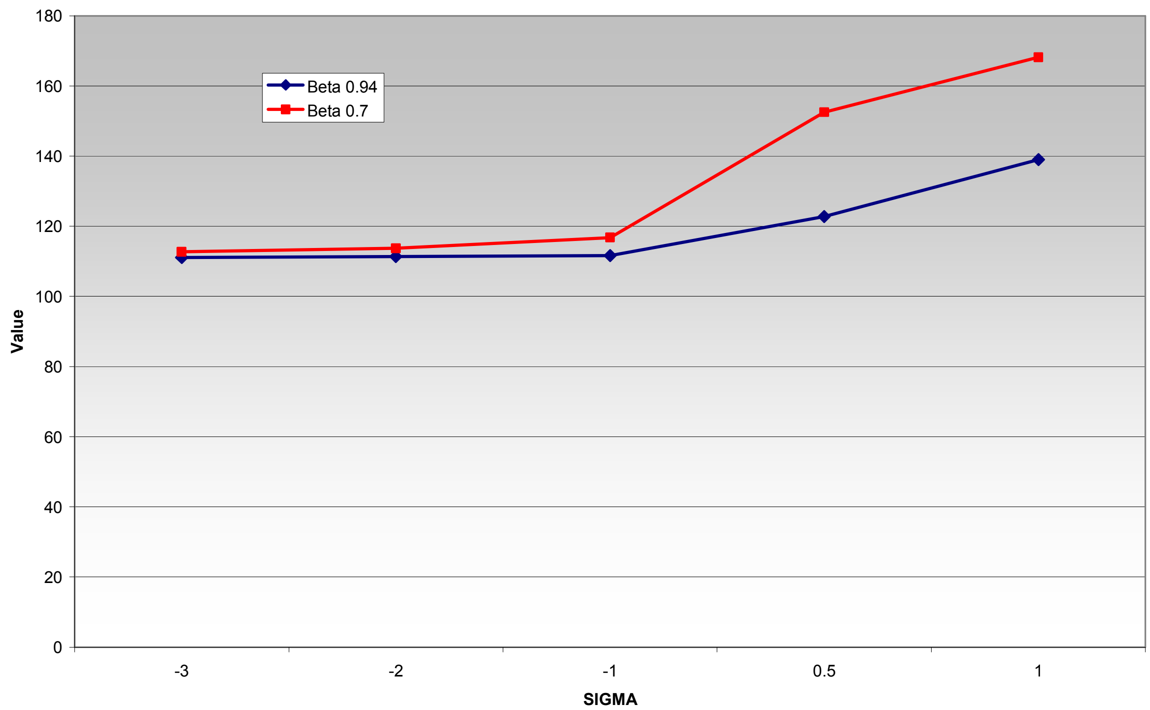


**Figure 12: Utility at high levels of knowledge sector productivity.**

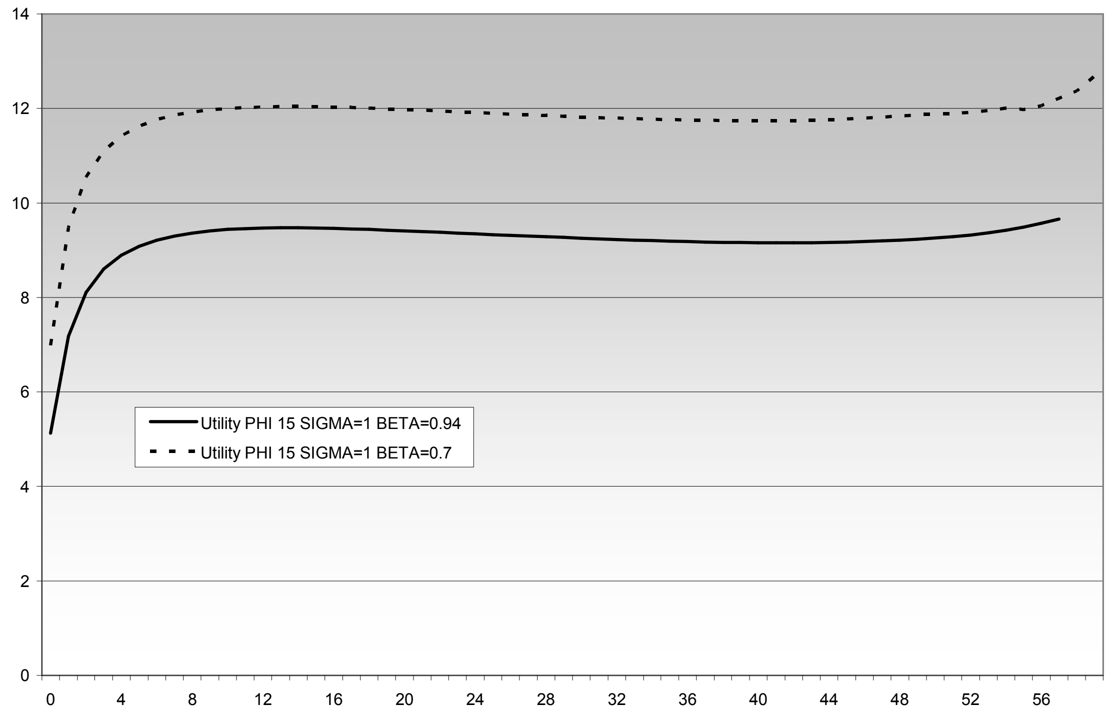



**Figure 13: Optimal utility path with a CES preferences.**

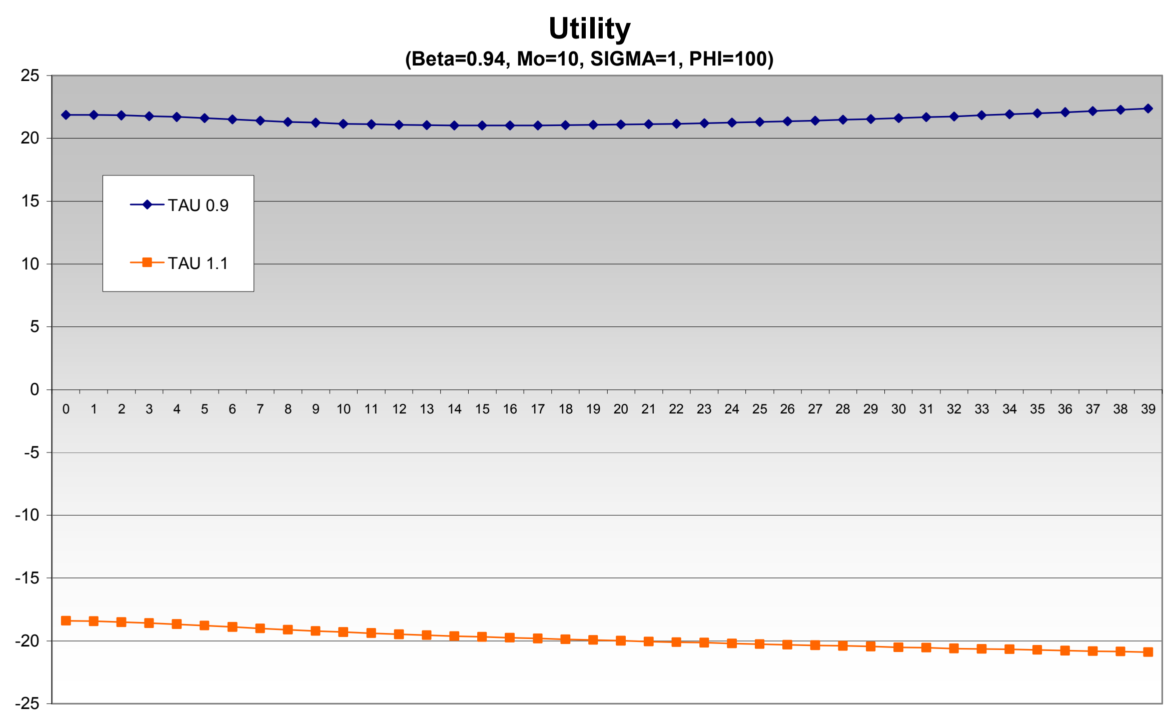
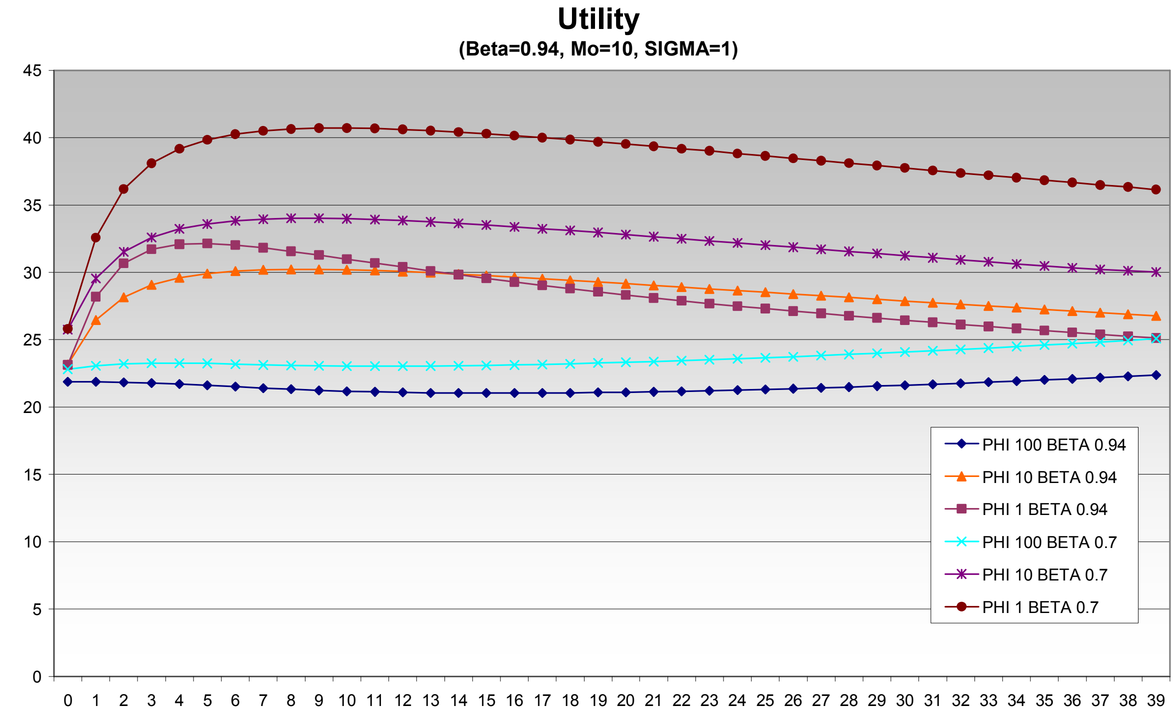


**Figure 14: Optimal utility path at varying productivity levels of the knowledge sector and shares of the depletable resource.**



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## APPENDIX: GAMS PROGRAMMES

**(A) Exogenous Technical Progress with Cobb Douglas Production Function**

```
$ontext
OPTION NLP      = minos5 ;

KB(N,TT)..      R*K(N,TT) =L= I(N,TT);
$offtext

** REPRESENTATIVE AGENT MAXIMIZATION PROBLEM WITH
** RENEWABLE AND NON RENEWABLE ENERGY RESOURCES

SETS            T               Time periods                                    /0*60/;

SCALARS
** Preferences NEED TO GET VALUES FROM LITERATURE
rho             Rate of time preference per year                                /.04/

** Technology
dk              Depreciation rate on capital per year                           /0.1/
alpha           Capital elasticity in production function                       /0.4/
beta            Non-renewable resource elasticity in energy production function /0.2/
fi              Productivity of human capital sector                            /0.1/
theta           Renewable energy extraction costs                               /0.2/

** Environment and emissions
gamma           Environmental absorption rate                                   /0.1/
pbar            Maximum pollution threshold                                     /10/;

* Definitions for outputs of no economic interest
SETS
tfir(t)
tfin(t);

PARAMETERS
dist(t)         Instantaeous rate of social time preference;
dist(t)=(1+rho)**(-ord(t));

* Defining Exogenous Learning by Doing (LBD)

PARAMETERS
GLbD            Yearly growth rate of LbD                                       /0.1/
EXM(T)          Exogenous LbD                                                   /0 1/
;

loop(t, EXM(t+1)=(1+GLbD)*EXM(T));

Display EXM;

* Unimportant definitions
```

```
tfir(t) = YES$(ORD(T) EQ 1);
tfin(t) = YES$(ORD(T) EQ CARD(T));

VARIABLES
y(t)                Output UNIT
c(t)                Consumption UNIT
p(t)                Stock of pollution UNIT
r(t)                Renewable energy resource UNIT
z(t)                Non-renewable energy resource UNIT
k(t)                Physical capital UNIT
s(t)                Stock of non-renewable resource UNIT
x(t)                Pollution change
I(T)                Investment
EN(T)               Total energy produced
*mu(t)              Exogenous LBD multiplier
*m(t)               Stock of human capital UNIT
*RATIO(T)           RATIO Z Q

UTIL                Objective function;

POSITIVE VARIABLES Y, R, Z, P, C, K, S, I,EN;

EQUATIONS
** Equations of the model
QY(t)               Output equation
QP(t)               Pollution balance equation
QP_FIRST            Pollution at first point in time
QK(t)               Man made capital balance equation
QK_FIRST            Capital at first point in time
QK_LAST             Capital at last point in time
QS_FIRST            Depletable resource first period
QS(t)               Depletable resource stock equation
QUTIL               Objective function
QX(t)               Pollution change maximum minus unit level
QC(T)               Budget constaint
QEN(T)              Total energy
;
QP_FIRST("0")..     P("0")=e=1;
QP(t+1)..           p(t+1)=E=z(t)+(1-gamma)*p(t);
QX(t)..             x(t)=E=(pbar-p(t));

QK_FIRST("0")..     k("0")=E=20;
QK_LAST("60")..     RHO*k("60")=L=I("60");
QK(t+1)..           k(t+1)=E=K(T)*(1-DK)+I(T);

QS_FIRST("0")..     S("0")=E=32;
QS(t+1)..           s(t+1)=E=s(t)-z(t);

QEN(T)..            EN(T)=E=(Z(t)**BETA)*((EXM(t)*R(t))**(1-BETA)) ;
```

```
QY(t)..                 Y(t)=E=(K(t)**alpha)*(EN(T)**(1-alpha));

QC(T)..                 C(T)=E=Y(T)-I(T)-THETA*R(T);

QUTIL..                 UTIL=E=sum[t,dist(t)*(log(c(t))+log(x(t)))];

**  Lower bounds on variables
K.lo(t)        = 0.001;
C.lo(t)        = 0.001;
P.lo(t)        = 0.001;
R.lo(t)        = 0.001;
Z.lo(t)        = 0.001;
S.lo(t)        = 0.001;
*M.lo(t)        = 0.9;
X.lo(t)        = 0.001;
p.lo(t)        = 0.001;

**  Upper bounds on variables
*M.up(tfin(t))        = 1000;

** initial values
*P.l(T)       = 0.1;
*S.fx("60")     = 0.001;
*Z.FX("60")     = 0.0000001;
*Z.L("1")       = 0.2;
*R.fx("0")       = 2.5 ;
*K.L("0")       = 4 ;
*Y.L("0")       = 0.21 ;
*EN.L("0")       = 4.121 ;
*I.L("0")       =0.01 ;

** Solution options
option iterlim = 99900;
option reslim = 99999;
option solprint = on;
option limrow = 0;
option limcol = 0;
option nlp = minos;

* Optimal run
MODEL TEST /all/;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
```

```
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;

* Reporting of variables
PARAMETER REPORT SOLUTION SUMMARY;
report(t, "k") = k.l(t);  report(t, "c") = c.l(t);  report(t, "y") = y.l(t);
REPORT(T, "I") = I.L(T);  REPORT(T,"Z") = Z.L(T); REPORT(T,"R")=R.L(T);
REPORT(T,"P")=P.L(T); REPORT(T,"S")=S.L(T);  REPORT(T,"EN")=EN.L(T);
*REPORT(T,"M")=M.L(T);
display R.l, en.l;

DISPLAY util.l;
display R.M, en.M, EXM;
DISPLAY REPORT;
```

**(B) Endogenous technology with varying consumer and producer functional forms**

```
** REPRESENTATIVE AGENT MAXIMIZATION PROBLEM WITH
** RENEWABLE AND NON RENEWABLE ENERGY RESOURCES


 SETS        T        Time periods                    /0*60/;

 SCALARS
** Preferences
 rho          Rate of time preference per year          /.04/

** Technology
 dk          Depreciation rate on capital per year      /0.1/
 alpha       Capital elasticity in production function  /0.4/
 beta        Share of depletable resource               /0.94/
 fi          Productivity of human capital sector       /10/
 theta       Renewable energy extraction costs          /0.2/
 tau         Intertemporal elasticity of substitution   /0.9/
 sigma       CES substitution elasticity                /1.0

** Environment and emissions
gamma          Environmental absorption rate      /0.1/
pbar          Maximum pollution threshold       /10/ ;

** Environment and emissions
 gamma       Environmental absorption rate              /0.1/
 pbar        Maximum pollution threshold                /100/ ;

* Definitions for outputs of no economic interest
 SETS
 tfir(t)
 tfin(t);

 PARAMETERS
 dist(t)         Instantaeous rate of social time preference;
 dist(t)=(1+rho)**(-ord(t));

* Unimportant definitions
 tfir(t) = YES$(ORD(T) EQ 1);
 tfin(t) = YES$(ORD(T) EQ CARD(T));

 VARIABLES
 y(t)            Output UNIT
 c(t)            Consumption UNIT
 p(t)            Stock of pollution UNIT
 r(t)            Renewable energy resource UNIT
 z(t)            Non-renewable energy resource UNIT
 k(t)            Physical capital UNIT
```

```
 s(t)          Stock of non-renewable resource UNIT
 x(t)          Pollution change
 I(T)          Investment
 EN(T)         Total energy produced
 mu(t)         Exogenous LBD multiplier
 m(t)          Stock of human capital UNIT
 UTIL          Objective function;

POSITIVE VARIABLES Y, R, Z, P, M, C, K, S, I,EN;

 EQUATIONS
** Equations of the model
 QY(t)                 Output equation
 QP(t)                 Pollution balance equation
 QP_FIRST              POLLUTION AT FIRST POINT IN TIME
 QK(t)                 Man made capital balance equation
 QK_FIRST              CAPITAL AT FIRST POINT IN TIME
 QK_LAST               CAPITAL AT LAST POINT IN TIME
 QS_FIRST              Depletable resource first period
 QS(t)                 Depletable resource stock equation
 QUTIL                 Objective function
 QX(t)                 Pollution change maximum minus unit level
 QC(T)                 BUDGET CONSTRAINT
 QEN(T)                TOTAL ENERGY
 QM_FIRST              Human capital first period
 QM(t)                 Human capital equation ;

 QP_FIRST("0")..       P("0")=e=1;
 QP(t+1)..             p(t+1)=E=z(t)+(1-gamma)*p(t);
 QX(t)..               x(t)=E=(pbar-p(t));
 QK_FIRST("0")..       k("0")=E=20;
 QK_LAST("60")..       RHO*k("60")=L=I("60");
 QK(t+1)..             k(t+1)=E=K(T)*(1-DK)+I(T);
 QS_FIRST("0")..       S("0")=E=32;
 QS(t+1)..             s(t+1)=E=s(t)-z(t);
 QM_FIRST("0")..       M("0")=E=100;
 QM(t+1)..             M(t+1)=E=(1+fi*R(t))*M(t);

** CES ENERGY PRODUCTION FUNCTION with PRODUCTION SHARES
QEN(T)..       EN(T)=E=(beta*(Z(t)**sigma)+(1-beta)*((M(t)*R(t))**sigma))**(1/sigma);

** CD ENERGY PRODUCTION FUNCTION
*QEN(T)..      EN(T)=E=(Z(t)**BETA)*((M(t)*R(t))**(1-BETA)) ;

 QY(t)..       Y(t)=E=(K(t)**alpha)*(EN(T)**(1-alpha));

 QC(T)..       C(T)=E=Y(T)-I(T)-THETA*R(T);

** LOGARITHMIC UTILITY FUNCTION
 QUTIL..       UTIL=E=sum[t,dist(t)*(log(c(t))+log(x(t)))];
```

```
** CRRA UTILITY FUNCTION
* QUTIL..       UTIL=E=sum[t,dist(t)*(((c(t))**(1-tau)/(1-tau))+((x(t))**(1-tau)/(1-tau)))];

**  Lower bounds on variables
K.lo(t)        = 0.001;
C.lo(t)        = 0.001;
P.lo(t)        = 0.001;
R.lo(t)        = 0.001;
Z.lo(t)        = 0.001;
S.lo(t)        = 0.001;
M.lo(t)        = 0.9;
X.lo(t)        = 0.001;
p.lo(t)        = 0.001;

**  Upper bounds on variables
M.up(tfin(t))        = 1000;

** initial values
*P.l(T)      = 0.1;
*S.fx("60")    = 0.001;
*Z.FX("60")    = 0.0000001;
*Z.L("1")      = 0.2;
R.L("0")      = 2.5 ;
K.L("0")      = 4 ;
Y.L("0")      = 0.21 ;
EN.L("0")      = 4.121 ;
I.L("0")      =0.01 ;
*ratio.FX(T)$(ORD(T) GE 2)    = 0.3;

** Solution options
option iterlim = 99900;
option reslim = 99999;
option solprint = on;
option limrow = 0;
option limcol = 0;
option nlp = minos;

* Optimal run
MODEL TEST /all/;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;
```

```
SOLVE TEST using nlp maximizing UTIL;
SOLVE TEST using nlp maximizing UTIL;

* Reporting of variables
PARAMETER REPORT SOLUTION SUMMA RY;
report(t, "k")=k.l(t);  report(t, "c")=c.l(t);  report(t, "y")=y.l(t);
 REPORT(T, "I")=I.L(T);  REPORT(T,"Z")=Z.L(T); REPORT(T,"R")=R.L(T);
 REPORT(T,"P")=P.L(T); REPORT(T,"S")=S.L(T);  REPORT(T,"EN")=EN.L(T);
 REPORT(T,"M")=M.L(T);

display R.l, en.l, m.l;
DISPLAY util.l;
display R.M, en.M, m.M;
DISPLAY REPORT;
```