Governance under Time Inconsistency and Limited Credibility:

What can be learned from Monetary Policy for Climate Policy?

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Working Paper - Comments Welcome

Abstract
This paper investigates the parameters and circumstances that determine the time inconsistency of climate policy, such as a carbon tax or a cap and trade system. If the best response to a problem changes over time although the problem itself does not change, the response is "time inconsistent". Climate policy is time inconsistent because capital investments are irreversible. Once investments are sunk, profit-maximizing firms react differently to tax changes than before. Energy consumption reacts stronger on tax changes, and greenhouse gas emissions react weaker. As a consequence, the optimal tax is lower once investment is sunk. Firms anticipate this relaxation of climate policy and are reluctant to invest in the first place. This results in an inefficient allocation with too much energy consumption, little abatement, and too little technology investments. Institutional arrangements (*polities*) such as an independent "Carbon Bank" are discussed as a remedy. Also different types of *policies* are discussed. It is argued that especially feed-in-tariffs can provide a feasible fix for time inconsistency because in contrast to carbon taxes they establish property rights.

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List of Acronyms

CBI	Central Bank Independence
CCC	Committee on Climate Change
CCS	carbon capture and sequestration
CDM	Clean Development Mechanism
COP	conference of parties
CS	Consumer Surplus
ECB	European Central Bank
EEG	Erneuerbare Energien Gesetz
ETS	EU Emission Trading Scheme
FED	U.S. Federal Reserve
GHG	Greenhouse Gas
LoPo	Long-term Policy Problem
MCF	marginal cost of public funds
ppm	parts per million
UNFCCC	U.N. Framework Convention on Climate Change

1 Introduction

Time Inconsistency

If the best response to a problem changes over time although the problem itself does not change, the response is "time inconsistent". Take a illustrative example from university: A teacher wants her students to study, but dislikes grading exams. However, since an exam is the only possibility to make her students study, she is willing to give one. At the beginning of the term, she announces an exam for the end of the semester. At the morning of the exam, it will be optimal for her to cancel the exam to save her the trouble of grading and the students the trouble of writing. Students anticipate the deviation from the announcement and won't study in the first place.

Why it optimal for the teacher to announce an exam in the beginning and cancel it in the end? The reason is that in the mean time the students have studied (or not). Their decision is not reversible. In economic terms, the time investment is "sunk". Ex ante (before the investment is made), it is optimal for the teacher to give the exam. Ex post (after it is made), it is optimal not to give it.

All agents in this model have constant preferences and behave perfectly in line with rational choice theory. Nevertheless, the outcome is sub-optimal for the teacher. She prefers to have an exam to make her students study, but the announcement is not credible and this solution is not feasible.

A solution to this failure is commitment. If the teacher could commit to future behavior, e.g. by binding herself to a legal contract, the problem was circumvented and the "commitment solution" (announcing an exam and indeed giving it) is feasible.

Not only the action of private agents such as the teacher, but also governmental decisions can be time inconsistent. In this paper time inconsistency of climate policy is investigated.

Climate Policy

Anthropogenic climate change causes welfare-reducing damages to market and non-market goods. Because the damages from climate change are an externality, markets cannot solve the problem and policy is needed.

About a quarter of world wide anthropogenic Greenhouse Gas (GHG) emissions come from the power sector, that is from heat and electricity production. In some regions like the U.S. close to half of all emissions come from the power sector. This paper discusses mainly climate policy that is directed to the power sector.

The power sector depends heavily on its large and slowly depreciating capital stock, such as power plants and transmission technology. These investments consist in large parts of building and highly specific investment goods and are therefore practically irreversible.

As we have seen in the teacher model, irreversible investments can change the optimal response and render policy time inconsistent. To illustrate the implications of these long-term irreversible investment decisions for climate targets, take the case of the German electricity sector. At this moment, about 30 new coal-fired power plants are planned or under construction. If they are all built, these new plants alone will cause yearly emissions of about 190 million tons of CO_2 - throughout their lifetime of about 45 years. In her 2007 speech on climate change before the United Nations, chancellor Merkel has proposed to lower per capita emissions in Germany to two tons per year in 2050.[1] The power plants under construction and in planning today alone would cause per capita emissions of almost three tons, even if transport, industry, and agriculture would reduce their emissions to zero. If they are all build, no one could sensible propose a target of 2 tons per capita anymore.

Climate policy might be dynamically inconsistent, because investment decisions in the power sector are irreversible. The optimal policy for government changes once investments are sunk. Firms anticipate that policy will change ex post and behave according to the anticipated policy.

The Double Goal of Climate Policy

I argue that governments want to protect the climate, but dislike high energy prices. The reason for protecting the climate is to prevent dangerous climate change. But what is the reason to dislike high energy prices? There are ethical, economical, and political reasons. Ethically, high energy prices are regressive since they hit poor families harder than rich households. There are many good ethical reasons to dislike economic inequality. Economically, high taxes distort decisions of private agents and cause “dead weight losses”.

Politically, high energy prices are quite dangerous. For some reason or the other, energy prices are discussed very emotionally all around the globe. Gas prices are probably the most heavily debated prices at all. Two examples to illustrate this are the 1989 *Caracazo* in Venezuela and the history of the German Green Party

[1] http://www.bundeskanzlerin.de/nn_5296/Content/DE/Rede/2007/09/2007-09-25-rede-bkin-leaders-dialogue.html

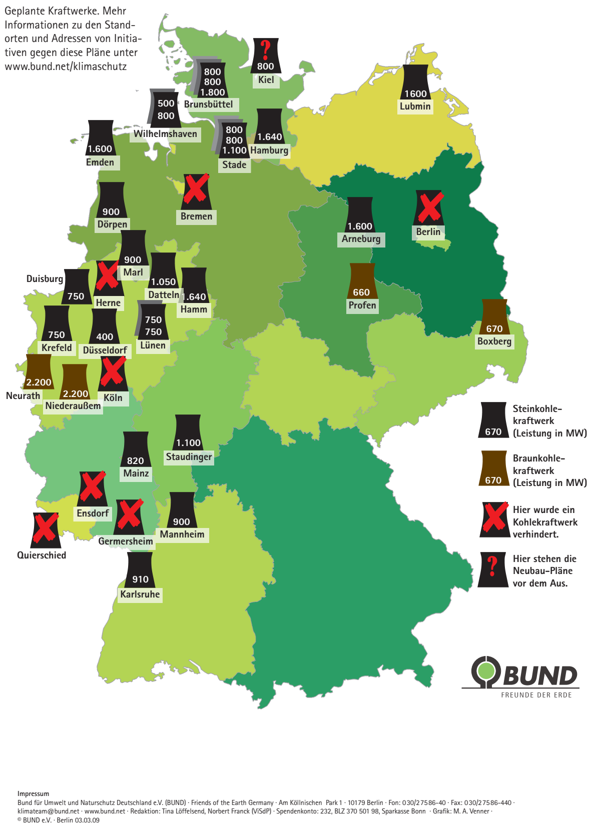

Figure 1: Coal-fired power plants currently planned or under construction.

during the 1990s. In Venezuela, the abolition of gas subsidies in late February of 1989 lead to spontaneous eruptions of protest and violence. During the protests up to 1000 people were killed and the conflict caused severe damages to the entire political system. Finally, the subsidies were re-introduced and the gas price is fixed at about $0.06 per liter ever since. In Germany, the Green party decided on the 1998 Magdeburg party convention to aim at a gas price of 5 marks per liter within the following 10 years, a 300% increase. In the elections that followed the party suffered landslide losses.

But not only gas prices, also electricity prices are highly political. The latest incidence when this could be observed directly in Germany in 2007. Rising primary energy prices and the introduction of the EU Emission Trading Scheme (ETS) caused the final price for electricity to skyrock. At the same time, the large power suppliers generated record profits. Consequently, a huge political debate about "windfall profits" emerged during summer 2007. This debate had direct consequences on the future regulation of the ETS.

Thus it is a reasonable assumption that the government wants to protect the climate, but dislikes high energy prices.

The Direction of Time Inconsistency

If climate policy is dynamically inconsistent, what is the direction of the bias? Will policy be too loose or too tight compared to the welfare optimum? The answer is that most probably it will be inefficiently soft.

Considerer the following scenario: The regulator announces tight climate policy, such as a high carbon tax or a stringent cap in a cap and trade system. Firms invest in low-carbon technologies such as renewable energy, energy efficiency, and carbon capture and sequestration (CCS). Once these investments are made, government softens climate policy to lower energy prices. Doing so the government can get both, climate protection *and* low energy prices. For the government, this looks like the best of all worlds.

But energy firms and potential investors understand the optimization problem of the government and anticipate the deflection from the pre-announced policy path. They know their investments are irreversible and understand how dependent they are from future policy changes. They realize the danger of not being able to recuperate capital costs after investments are sunk and do not invest in the first place.

This leads to a socially inefficient outcome where energy prices are too low, too little GHG abatement is done, and too little is invested in low-carbon technologies. We might even end up in the worst of all worlds - high energy prices but little GHG mitigation because firms are rationally reluctant to invest.

Is this Realistic?

Is it reasonable to suspect the government to deviate from a pre-announced policy path? Image a scenario in 2030. A deep economic recession has lead many middle-income families fall close to poverty. Energy prices have been steadily increasing during the last decades and make up a large part of households' expenditures. At the same time utility firms report record profits.

At the peak of the crisis, populist parties all over Europe start to demand lower electricity prices. They claim that, given the increasing inequality and rising poverty rates obtaining electricity at a "reasonable price" is the right of every European. They argue, oligopolistic suppliers generate "tremendous and immoral windfall profits" while incurring hardly any operational costs, since "the wind blows for free and sun shines for free". They demand price regulation and lower energy taxes. Such a campaign would probably be politically very attractive and hard to resist by other parties.

It is actually not important if such a scenario will or even could emerge. To make the point, it is only important that today's investors *believe* this indeed is realistic. Given the experience RWE, E.On, Vattenfall, and EnBW made during the last years, I think it is highly plausible for them to believe such a scenario.

Monetary Policy

While being widely neglected in environmental policy, the time inconsistency problem is well studied in monetary policy. Here, the trade-off is not between GHG mitigation and energy prices, but between inflation and unemployment. The government is inclined to increase the money supply in order to stimulate demand and increase employment. As an unwarranted and costly consequence, inflation increases. This model works only because labor contracts are fixed in nominal terms. The nominally sticky labor contracts are the irreversible element of the monetary policy model, comparable to fixed investments in climate policy and sunk time investments in the teacher model.

The famous solution proposed in monetary policy is to hand over the decision-making on monetary policy to an independent central bank. Autonomous central banks, having a stable price level as the only target, are in theory able to reach the optimal outcome. This is similar to the "commitment solution" of the teacher. Thus institutional design, or polity, is used to solve the time inconsistency problem.

Carbon Bank

Some first steps in a similar direction were recently made in the UK when the Climate Change Act was established in late 2008. Under this act, the Committee on Climate Change (CCC) was founded as an independent body to advise the Government on emissions targets, and to report to Parliament on progress made in reducing greenhouse gas emissions. The CCC is made up of experts from the fields of climate change, science and economics. The CCC produces and publishes 5-year "carbon budgets", medium-term goals for national total emissions. The CCC hopes to guide policy making and make future climate policy more credible. The establishment of the CCC can be viewed in the British tradition of autonomous policy advice institutions, e.g. in labor market regulation. It does *not*, however, directly set policies as central banks do.

This leads to the central question of this paper: Is a "carbon bank" a solution to the time inconsistency problem in climate policy? What can be learned from monetary policy to fight the problem of time inconsistency in climate policy?

Outline of the Paper

The paper consists of seven sections after this introduction. Section two gives an overview about the science, economics, and politics of climate change. Section three focuses on the concept of time inconsistency. The central "ingredients" for time inconsistency are identified and time inconsistency is demarcated from other concepts such as changing preferences or self-interested governments. Section four explains the "classical model" of time inconsistency in monetary policy as introduced by Kydland and Prescott (1977). Other applications such as income taxation and patents are also touched upon. In section five, the time inconsistency literature on climate policy is reviewed. The scope of the literature is very limited. Nevertheless, three core papers are identified and presented in detail.

Section six is the core of the paper. Here, a new analytical model of the electricity market under carbon taxation is developed. Three channels of time inconsistency are modeled: Economic surplus, tax revenues, and the climate externality. It is shown that under plausible parameters time inconsistency exists and causes a downward bias on carbon taxes. Section seven discusses remedies. Both polity-based and policy-based commitment devices are analyzed. Section eight concludes and suggests some lines of future research.

Central Results

The model from section six yields several important results with respect to time inconsistency of climate policy. If investments respond positively on carbon taxation, and public finance plays little role, time inconsistency causes a downward bias on carbon taxes. Under a Cobb-Douglas specification, investments respond positively on carbon taxes if the price elasticity of demand is smaller than unity in absolute value, which seems to be the case empirically. Thus the direction of time inconsistency is negative. Climate policy will be laxer than necessary to obtain the welfare optimum.

Due to the downward bias of the tax, final energy consumption is too high compared to the welfare optimum, emissions are too high, and investment is too low. There is an important and clear policy recommendation from these findings: The danger is that climate policy is too lax. Policy should be designed in a way that credibly prevents softening.

How can policy become credible? Polity-based commitment devices such as delegation to an independent body seem to work quite well in monetary policy. Because time horizons are several dimensions larger in climate policy than in monetary policy, delegation probably is more difficult in climate policy. Policy-based commitment devices seem to be more promising. Especially policy that establish property rights are somewhat shielded from being watered down ex post and consequently are more credible. Feed-in tariffs as well as research subsidies are prominent examples of policies that establish property rights.

2 Climate Change

This sections presents a dense summary of the state of knowledge of the science, economics, and politics of climate change. Readers familiar to the field might well continue with section 3.

2.1 Science

The climate system consists of the four spheres atmosphere (air), lithosphere (ground), hydrosphere (water), and biosphere (life). Anthropogenic climate change affects all of them, including humans and their social systems. The current scientific state of knowledge on climate change is thoroughly summarized in the current IPCC assessment report (IPCC 2007a, IPCC 2007b, IPCC 2007c, IPCC 2007d).

GHG Emissions

The most important way men affect the climate is through the emission of Greenhouse Gases (GHG) into the atmosphere. Anthropogenic GHG emissions since the beginning of the Industrial Revolution and large-scale burning of fossil fuels have lead to a net increase of radiative forcing of 2.5 W/m^2. Other ways humans influence to climate include the change of albedo through land-use change (crop fields reflect more sun rays back to space than woods) with a cooling effect of 0.1 W/m^2 and the emission of aerosols to the atmosphere (mainly SO_x from coal-fired power plants) with a cooling effect of 1.2 W/m^2 (IPCC 2007b). While albedo changes and aerosol emissions affect the climate primarily locally and regionally, GHGs disperse quickly around the globe. It takes centuries to millennia to reduce the atmospheric CO_2 concentration through silicate weathering.

The most important anthropogenic GHG gas is carbon dioxide (CO_2), making up 74% of all human emissions, followed by methane (CH_4) with 17% and nitrous oxide (N_2O) with 9%. More than half of all methane emissions are from agriculture (mainly watered rice fields and ruminants) and virtually all nitrous oxide stems from agriculture (a consequence of nitrate fertilizing). Of the carbon dioxide emissions, 33% comes from power and heat generation, and 15% from industry and transportation each. Close to 25% is from land use change, mainly tropical deforestation.[2] CO_2

[2] Data come from the World Resource Institute (http://cait.wri.org), the most reliable source for global GHG emissions. CAIT is a seconday data provider who pooles different sources of emission data. Primary data are mainly from official UNFCCC reports, IEA, and Houghton (2003b). For detailed methodology decription see the supporting documentation at http://cait.wri.org/links.php. Reference year is 2005.

emissions from power, heat, industry, and transportation almost entirely comes from burning fossil fuels such as coal, oil, and gas. Burning one ton of fossil fuels produces roughly 2.5 tons of CO_2. Emissions from land-use change come mainly from the oxidation of wood biomass and loss of soil carbon. In 2005, total global emissions were 38 GtCO_2e or 6 tons per capital. Since 1850, atmospheric CO_2 concentration has increased by more than a third from 280 parts per million (ppm) to 390 ppm.

Damages

Mainly due to the increase in the GHG concentration, global mean temperature has increased by about 0.8°C since pre-industrial levels. IPCC scenarios predict the temperature to increase another 2-4°C by the end of the century if no policy intervention takes place. Potentially adverse effects of such a temperature increase include spatial and temporal shifts in precipitation patterns, reduced agricultural and silvicultural production, loss of biodiversity, acidification of the oceans through uptake of CO_2, sea level rise and floodings, more frequent and more severe extreme weather events, increased energy consumption for cooling, and increased human mortality and morbidity due to temperature increase, expansion of tropical diseases, and climate-induced famine (Nordhaus and Boyer 2000, Tol 2002a, IPCC 2007c).

Feedbacks and Tipping Elements

The climate system is highly complex, and non-linearities as well as positive feedback effects are pervasive. The behavior of many subsystems may change dramatically and abruptly if some threshold is reached. These unstable equilibria are sometimes called "tipping elements" of the climate systems.

Example include the Greenland ice shield: Today large parts of the shield are more than 2000 meters above sea level, and due to fresh snow albedo is very high. If the temperature rises, snow will melt quicker, and more and more black carbon particles will remain on the surface and speed up local temperature increase. This is the first positive feedback-loop. There is another positive feedback at work. Melting causes the surface to decline. Since lower altitudes above sea level are warmer, the surface temperature increases further. Taking these positive feedback loops into account, melting could happen very quickly once a certain temperature is reached.

Other tipping elements include the North Atlantic Deep Water Formation and the Gulf Stream, and Monsoon stability in Western Africa as well as India, and Siberian permafrost (Lenton et al. 2008). The uncertainty about such tipping elements lead the European Union to aim for limiting global warming to 2° above pre-industrial levels. This translates to a limit of about 490 ppm atmospheric CO_2e concentration.

Distribution

Both GHG emissions and damages from climate change are highly unevenly distributed around the globe. Per capita emissions range from 50 tons per year in some oil-rich Arab countries to 25 tons in the U.S. and 11 tons in the European Union, down to to less than one ton in some African and South Asian countries. At the same time, many of these low emitting countries are and will be hit most severely by consequences of climate change. This is because agriculture represents a large fraction of the income and because these countries are prone to desertification or endangered by sea level rise.

2.2 Economics

Cost-Benefit Analysis

Economists have tried to weigh the costs of climate change with the cost of GHG mitigation doing cost-benefit analysis to find the socially optimal magnitude of climate protection. Nordhaus (2008) finds it optimal to limit global warming to 3.6° above pre-industrial levels. Stern (2006) argues a much more stringent cap of 1.5° is optimal. While uncertainties remain large and there is considerably debate about the optimal level, it is sometimes overlooked that virtually all natural and social scientists agree that substantial mitigation is warranted: The optimal amount of climate policy is for sure larger than zero and certainly larger than today's level.

Some have believed that the limited availability of fossil fuels itself constrains emissions enough to prevent dangerous climate change. Edenhofer et al. (2009a) compare fossil resources with the CO_2 capability of the atmosphere and conclude that there are vastly more resources available than men can burn without leading to extreme global warming. The carbon stored in coal alone is about 12,000 Gt. To limit global warming to 2° only 1,000-2,000 Gt can be emitted.

The Transition to a Low-Carbon Economy

The only feasible way to mitigate climate change is to reduce GHG emissions.[3] There are three principle ways to reduce emissions:

[3] So called "Geoengineering" is the other option. It has been proposed, for example, to inject large amounts of aerosols to the atmosphere to reflect sun rays back to space. For convincing reasons why this does not work see Robock (2008).

- increasing energy efficiency
- low-carbon energy generation
- substituting of low carbon for high carbon consumption goods
- reducing consumption compared to the business as usual case

Increasing energy efficiency include upstream (generation) efficiency of electricity, downstream (consumption) efficiency of electricity, increased transport efficiency and fuel switch, biomass for heating, electricity, and transport, and reducing deforestation and forest degradation. Low-carbon energy generation covers renewable energy suppliers such as wind and solar power as well as CCS.

Substitution of consumption goods means, inter alia, eating vegetarian, riding trains not cars, using video-conferences for business travel, and spending holidays locally. In any case, most (but not all) of these changes are welfare-reducing. In other words, climate protection is costly in terms of utility from consumption.

To limit the costs of GHG mitigation, increasing energy efficiency plays a crucial role. During the next decade, the energy system of today's industrialized countries will have to be completely conversed. A whole range of new and significantly improved technologies are needed, especially wind and solar power generation. It is not only power plants that will have to be fundamentally changed, but also the grid and storage technologies. For example, to link areas with large potential for renewable resources to areas with large demand, long distance direct current transmissions lines have to be constructed. This requires a complete turnover of the existing capital stock to embody those technologies.

The Economics of Externalities

The first fundamental theorem of welfare economics states that the market equilibrium under perfect competition is Pareto-efficient. This means that no agent can be made better off without making someone else worse off. Under market failures, however, this result does not hold. They cause the market to be inefficient, leaving room for state regulation to improve efficiency.

So called positive and negative "externalities" (or external effects) are a major type of market failure. Negative externalities mean that the deciding agent gets all benefits, does not have to bear all costs of his action. Other market failures are public goods, asymmetric information, and market power. External effects are pervasive, and since transaction costs often prevent private agents to find efficient solution for internalization, state intervention is often warranted (Coase 1960).

Sir Nicholas Stern (2006) famously called climate change "the greatest market failure the world has seen". While the economic agents that make the decision to burn fossil fuels or to use carbon-free substitutes usually obtain the gains from burning fossil fuels such as the profit from selling electricity, they do not bear the costs related to climate change such as a flooding in Tuvalu. These costs are dispersed widely across space (globally) and time (on future generations). Because firms and individuals do not take into account the harm they cause on others and on future generations, they burn too many fossil fuels.

Some overreaching institution with discretionary power, such as the state, has to intervene in free markets in order to establish efficiency. In rational choice theory market failures such as external effects are indeed the major justification for the existence of states and governments.

Command & Control vs. Incentive Regulation

States can either use their discretionary power to ban or to prescribe certain behavior, or they discourage harmful behavior by increasing its relative price. The difference turns out to be fundamental.

Command and Control regulation determines not only *how much* carbon has to be saved, but also *the way* this has to be done. A recent example for Command and Control regulation in climate policy is the prescriptions of light bulbs in the European Union from 2010 on ("Ecodesign-directive" 2005/32/EC). Another is the limitation of car emissions to 130 gCO_2/km on fleet average. Such laws are in general economically inefficient. Why is this the case? It might well be that some people value light bulbs highly so that they are willing to pay a lot for them. Indeed, hoarding of light bulbs despite its threefold increased price in Great Britain where bulbs are prohibited since 2008 indicates that this is indeed true.[4] These people might be much more willing to mitigate GHG emissions by, say, driving less, avoiding flights, eating vegetarian, heating their homes less, or any other efficiency investment or change in their consumption pattern. The prohibition of light bulbs does not allow people to decide on their preferred way to reduce emissions. The same GHG mitigation could be achieved with less loss in utility. In other words, the policy is not Pareto-efficient.

Regulation by incentives attaches a price to carbon. In economic jargon, it "internalizes" the external effect by making the originator of emissions pay the damage he causes on others. Facing these costs, he will reduce his harmful activities

[4] http://news.bbc.co.uk/1/hi/magazine/7480958.stm

to efficient levels. As discussed more in detail in section 5.3, there are two principle ways to implement incentive-regulation: A carbon tax or a cap and trade system. Under a carbon tax, every polluter pays a tax per ton of CO_2 emitted to the state. Under a cap and trade system the state auctions emission permits (allowances). To emit one ton of CO_2, the emitter has to hand over one permit to the state. In the meantime, permits can be trade between firms. Both regimes attach a price to carbon, thus I call the entire set of policy "carbon pricing".

In a general model, both systems yield the identical outcome in terms of emissions, efficiency, and state revenue, if the price and the number of permits are set accordingly. The tax rate will coincide with the permit price, and all "cheap" mitigation options (cheaper than the tax rate / permit price) will be conducted while no "expensive" option will be used. In economic terms, the marginal abatement costs are equalized across mitigation options. This is the necessary condition for social efficiency.

2.3 Politics

Climate Change as a LoPo problem

Detlef Sprinz (2008) defines Long-term Policy Problems (LoPos) as "public policy issues that last at least one human generation, exhibit deep uncertainty exasperated by the depth of time, and engender public goods aspects both at the stage of problem generation as well as at the response stage." Climate change is the archetype of such a problem. More specifically, three aspects make climate change an outstanding challenge: its global good characteristic, long time frames, and uncertainty.

First, climate protection is a near-perfect public good across space. Virtually every human in the world is affected if anyone emits CO_2, since GHGs are dispersed globally and the climate system operates at a global scale. Thus states, covering only small fractions of the world population, are not the appropriate level to organize GHG mitigation. It is not only that individual agents can free-ride on other agents' mitigation efforts, but whole countries can free-ride on other counties' actions. Intergovernmental negotiations like the U.N. Framework Convention on Climate Change (UNFCCC) process try to overcome this collective action problem. But climate protection is also a public good over time. GHG remain in the atmosphere for centuries, and changes in the climate system will not undone within millennia. So far, no institution has been designed to represent future generations in climate policy making.

Second, both damages of climate change and costs of mitigation efforts take place largely in the far-distant future. Economists use time preference (discount) rates to compare costs and damages over time. With a positive discount rate damages and costs are valued the less the farer in the future they appear. But the theory of discount rates in economics has been developed for shorter time frames and are not well suited to cover several generations. Often, long-term interest rate of riskless government bonds are used to proxy social rates of time preference. If these rates (3-6%) are used, damages that occure after the year 2050 play only very little role in cost-benefit analysis. Damages that happen more than a century in the future are valued so little that they can be ignored. Intergenerational discounting is one of the current hot debates in climate economics. Especially the *Stern Review* (Stern 2006) has sparked a fierce debate, since a very low discount rate of 0.1% was used for damage estimates, which is inconsistent with other assumptions made in the analysis. Moreover, such a low discount rate is inconsistent with observed economic behavior as many economists have claimed. However, there are several good reasons to use a very low discount rate, for example unceraінty in future discount rates or the chance of extrem events (Nordhaus 2008, Weitzman 1998, Newell and Pizer 2003a, Heal 2009).

Finally, uncertainty is pervasive in climate change. Uncertainty can be classified into scientific uncertainty, economic uncertainty, and regulatory or policy uncertainty. Scientific uncertainty is uncertainty about the climate system itself, the climate sensitivity, about reaction on disturbances such as GHG emissions, about tipping elements, the behavior of oceans, the capability of ecosystems to adapt, and regional variation of climate. Economic uncertainty is lack of knowledge about future economic development and world population, about technological change and the future costs of mitigation technologies. Regulatory uncertainty is uncertainty about future policies, intergovernmental negotiations, the carbon price, and possible linking of carbon markets. A pretty trivial insight is that if uncertainty is pervasive, one should avoid too much path-dependency and lock-ins, leaving room to adjust for new information. However, a central result from the analysis below is that due to time consistency, commitment is welfare-improving. Thus there is a trade-off between combating time inconsistency and staying flexible to account for uncertainty.

Climate Policy

Climate policy is conducted on virtually all levels of governance. At the global level, multilateral negotiations take place mainly under the UNFCCC. Most climate policy in Europe is decided on the EU level, such as the ETS. But on the national level, also important policies are designed, for example the Erneuerbare Energien Gesetz (EEG). At the sub-national level, some state governments and cities try to develop their own climate policy.

At the 1992 Conference on Environment and Development in Rio de Janeiro (the so called ”Earth Summit”), the UNFCCC was established. On the third conference of parties (COP) to the UNFCCC in 1997, the Kyoto protocol was signed. The protocol includes legally binding commitment of 38 OECD and transition economies (“Annex I parties”) to cut their GHG emissions on average by 5.3% in 2008-12 compared to 1990. Caps are specified as national total emissions in terms of CO_2e, not as limits for individual gases, sectors, or activities. All Annex I parties except the U.S. and Kazachstan have ratified the protocol.

All major long lasting greenhouse gases are covered by the protocol except those regulated by the 1987 Montreal Protocol on the Ozone Layer.[5]

Non-Annex I countries’ emissions are not capped by the protocol, but emission reduction projects in those countries can be used to reduce Annex I emissions via the Clean Development Mechanism (CDM), reflecting the principle of ”common but differentiated responsibility” of countries to protect the climate. The CDM is one of three flexible mechanisms of the protocol (the others being emission trading and Joint Implementation), indicating the intention to make the protocol market-friendly and to seek for economic efficiency.

In early 2008 the European Council set the medium-term climate policy goals for Europe often summarized as “20/20/20 in 2020”. The goal is to reduce aggregate GHG emissions by 20% in 2020 compared to 2005. At the same time, energy efficiency per unit of GDP should be increased by 20% and renewables provide 20% of all primary energy sources.

The most important building block of European climate policy is the ETS. The ETS is a downstream, plant-based emission trading scheme with about 12.000 participants covering about half of all European CO_2 emissions. The first phase of trading has been completed in 2007 with a carbon price close to zero. Currently the second phase is in effect, and the rules for the third phase from 2013-2020 have been decided on in December 2008.

[5] Gases covered by the Kyoto protocol are carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, and various hydrofluorocarbons and perfluorocarbons (CO_2, CH_4, N_2O, SF_6, HFCs and PFCs). Gases covered by the Montreal protocol are halogenated hydrocarbons. Greenhouse gases not covered are water vapor (H_2O) and ozone (O_3). Anthropogenic sources of climate change other than GHG emissions, such as aerosol emissions or changed albedo, are not regulated.

3 Time Inconsistency of Optimal Plans

An optimal plan for the future that is not optimal once the future is reached is called "time inconsistent" or "dynamically inconsistent". In other words: time inconsistency emerges if the ex ante optimal policy is different ex post.

The teacher's problem

Take a commonly observed example from university life. Teachers want their students to study, but they dislike grading exams. Assume that announcing an exam at the end of a class is the only way to make the students study. At the beginning of the semester (period 0) the instructor announces if there is an exam or not. During the term (period 1) the students study, or they don't. At the morning of the exam (period 2) the teacher has the possibility to cancel the exam. The teacher prefers to have his students study and let them write an exam over no studying with no exam.

There are three sensible possible outcomes which I call the optimal (or first-best) solution, the commitment (second-best) solution, and the consistent (third-best) solution. In the optimal solution an exam is announces in period 0, students study in period 1, and then the exam is canceled in period 2. This solution is not feasible if students have rational expectations. They know their teacher dislikes grading, thus they know he will cancel the exam, the announcement is not believed and students do not study, and the teacher will cancel the exam. This is the consistent solution.

The commitment solution is worse than the optimal solution, but better than the consistent solution. Under commitment an exam is announced, the students study, and indeed the exam is written. This works only if the teacher has not longer the freedom to decide about cancellation in period 2. If he is still free to cancel the exam, the commitment solution is not feasible. Voluntarily giving up freedom about future decisions is called commitment. In this example it becomes clear that giving up freedom can be superior than keeping that freedom.

There is a fourth solution: no studying, and writing an exam. This "least-best" result is not compatible with utility-maximizing behavior of the teacher: There is no reason to write an exam for him. But this solution might appear if commitment was not believed by the students.

The ingredients for Time Inconsistency

In the teacher's problem the five core ingredients for time inconsistency appear.

1. The "regulating" agent aims for (at least) *two goals*: The teacher likes students

to study, but dislikes exams. In the case of policy the two goals often appear as one goal that can only be reached through the application of a distortionary instrument. Thus the regulator wants as much goals as possible, but using as little instrument as necessary. Thus Fisher (1980) concludes that time inconsistency "arises when the government does not have non-distortionary control instruments at its disposal."

2. The goals depend on the decisions of *another* ("regulated") agent: The teacher wants the students to study, but they decide themselves to study or not.

3. There is *stickiness* or durability in the decision variable of the regulated agent: The students study in period 1, but cannot reverse their time investments when the exam is canceled in period 2. This has also be called lock-in, sunk investments, or the ratchet effect.

4. There is *flexibility* in the decision variable of the regulating agent: The teacher can reverse his decision *after* the students have made their time investments.

5. Decisions of the regulated agent depend on future decisions of the first one and expectations are at least to some degree rational. If students simply believe the teacher's announcement, there is time inconsistency, but that does not lead to problems. Indeed, in the example above even the first-best solution would be possible. Time inconsistency becomes a problem if and only if the students understand the teacher's preferences and know he dislikes grading.

To sum up, time inconsistency needs a situation with (at least) two agents, (at least) two time periods, decisions depending on expectations, and interaction of agent's decisions.

It is important to note that three three characteristics of the problem are *not* necessary conditions for time inconsistency to emerge, although often believed to be: uncertainty, changing preferences, and a selfish regulator.

First, in the model of the teacher's problem there is no uncertainty about the future. There are no technological changes or any other unforeseeable events. We could even allow the agents to have perfect foresight. If agents are rational, there is also no uncertainty about the behavior of the teacher: everyone knows he will cancel the exam.

Second, the preferences of the agents do not change. Of course, changing utility functions over time can lead to dynamically inconsistent behavior. But this has not been modeled here: Preferences remain the same in all periods.

Third, the two agents involved do not have to have diverging interests (even though in the example above they did). When dealing with government regulation, however, it might well be that the government behaves like a social planer, reflecting exactly society's preferences.

You cannot change history

At a more fundamental level, the reason for time inconsistency is that current decisions cannot effect past decisions by other agents, but expectations about future decisions might well influence current decisions of other agents. In Stanley Fischer's (1980) words, "inconsistency is the result of the failure to optimize backwards".

Because past decisions cannot be reversed, they cease to be variables and become parameters exogenous to the maximization problem.

As Kydland and Prescott (1977) have put it, "the suboptimality arises because there is no mechanism to induce future policymakers to take into consideration the effect of their policy, via the expectations mechanism, upon current decisions of agents."

Commitment as solution

Commitment is to promise a specific behavior in the future. The degree to which this promise is believed is called credibility. As sketched out in the above example, commitment can be used to lessen the consequences of time inconsistency. If the teacher can commit to writing the exam, at least the second-best solution becomes feasible.

Committing, however, is a highly non-trivial issue. First, finding credible commitment devices is often hard - especially for governments. Second, for credibility, deflecting from commitment has to be costly (this is almost a definition of credibility in rational choice models). If new information appears or unforeseeable events happen, adjustment to the new situation is costly. Finally, the timing of commitment (the begin of a commitment period) is a decisive question.

To commit oneself to a certain future behavior means setting oneself voluntarily binding constraints. Commitment is to give up discretionary power. Designing such constraints is difficult because of the very fact agents have to be able to enter such a contract by their own will, but must not be able to leave it. In general, perfect credibility is not feasible. If the gain from breaking a contract is larger than the loss implied in the contract penalty, rational agents will deviate from it. The larger deflection costs are, the less probable it is that happens, and the more credible commitment is.

Private agents operating under the rule of law and freedom of contract might be able to sign a binding legal contract that works as a commitment device. The teacher in the above example might well sign a contract that obligates him to give an exam. This is credible because a court could force the teacher to fulfill the contract Sovereign states and their governments lack this option, since there is no one who could enforce such a contract. Governments can pass bills that promise certain future behavior, but bills can be undone. The more costly it is in political terms to change the rules, the more credible they are. Rules written down in the constitution are more credible than simple bills, which are more credible than decrees, because future governments had to spent more political resources to change it than to change a simple bill and a decree.

Another possibility is delegation. At universities, handing to choice of writing an exam or not over to an independent agent such as registrar's office is observed in practice. The office does not experience disutility from grading and thus has no incentive to cancel the exam. Delegating policy-making to institutions independent from the government is indeed the major remedy to time inconsistency proposed by economists.

In complex systems like the economy with a very large number of random and ill-understood processes at work, unforeseen events happen regularly. New information is available, technological constraints are moving, market structure changes, and policy evolves. This implies that in general optimal plans, including optimal policy, changes over time. Commitment makes adjustment to changes impossible. This implies there is a trade-off between commitment (which helps to solve the problem of time inconsistency) and flexibility (which is needed to find a new optimal solution under a changed environment). Higher costs of deflection imply higher credibility, but also higher costs if adjustment is indeed needed. Thus the optimal degree of commitment is finite.

Finally, timing is a serious issue. To make the point, assume that perfect commitment to a certain policy is both feasible and desirable. At period zero, when the commitment is spelled out, the policy is chosen optimal for today and all future. Since the future brings unforeseen events, however, most probably at any point of time in the future the policy path chosen is not longer optimal. How should society decide when it is the right moment to commit? In some sense, committing gives the current generation the right to design optimal policy, but denies the same right the same right future generations.

A special case of commitment is the build-up of credibility in repeated games. If the model is repeated infinite times and time preference is sufficiently low, repeated commitment can be a feasible solution. This resembles a cooperative Nash equilibrium in infinite supergames, a well-known result from game theory. The teacher, for example, might be inclined to give an exam if he has another class in the next year.

Endogeneity and Exogeneity of Expectations

When modeling time inconsistent behavior, the expectation of the regulated agent are taken as given by the regulating agent. They are fixed parameters, not endogenous variables. Why is this the case? After investments are sunk, expectations cannot be changed anymore. That means, *ex post* they are parameters. Rational regulators maximize their objective function at any point in time. After investments are sunk, they take expectations as given and maximize according to these constraints.

If the regulator could commit to some policy, he would choose a policy *ex ante* and stick with that solution even after investments are sunk. Ex ante, expectations can be changed. This is why expectations are taken as endogenous variables in the so called “commitment solution”.

Some clarification of terms

“Discretion” is the power of one agent to change his decisions. In the above example, the teacher had the discrete power to give an exam or not. Policy “rules” are a form of commitment where governments promise to behave according to simple predefined rules. As any commitment, these rules must be credible to have any effect on the time inconsistency problem. Much of the economic debate on time inconsistency in monetary policy has been titled “rules vs. discretion”.

Economists use the terms “first-best”, “second-best”, and so fourth to rank outcomes in terms of their desirability. The first-best outcome is the best outcome possible under the specific model with a specific sets of constraints at hand. Introducing a further constraint in general leads to the second-best outcome, if and only if that constraint is binding (Lipsey and Lancaster 1956). In the student-teacher example the first-best solution is studying, but not writing an exam. This could only be reached if the students could be forced to study by some costless instrument (thus Fisher (1980) calls this the “command optimum”). Since such an instrument is not feasible, but giving an exam is the only policy available, the second-best solution is studying and writing an exam. But due to time inconsistency not even the second-best solution is feasible. Because of the structure of incentives, preferences, and timing, and the absence of any credible commitment device the only feasible solution is “no studying, no exam”. This third-best solution still dominates no studying, but writing an exam.

In the models in the following sections “rational expectations” are assumed. Rational expectations are opposed to purely adaptive (based on historical observations) or exogenous expectations (based on variables not modeled). This expectation formation hypothesis assumes that agents know and take into account the decision problems of other agents. This implies that people do not make systematic errors, but they might of course well be wrong in models with uncertainty. On average, however, expectations are fulfilled.

To compare adaptive with rational expectations take again the university example, but now assume two consecutive terms. Under adaptive expectations the teacher knows in the second term his students will believe his announcement of an exam if he gives one in the first term, otherwise not. Thus he will give one in the first term, students will study in the second term, but he will cancel the second exam, since he prefers not to grade, and there is no third period that his behavior might affect. Under rational expectations students realize the teacher won't give an exam in the first period, because they know the teacher's optimization problem. Given that, they won't study. The same is true for the first term. Thus for rational expectations the agents involved have to understand the economic maximization problem their counterparts are facing.

The terms "ex ante" and "ex ante" refer to the point of time where investments (in time, capital, human capital, or technology) are made. Ex ante this decision, the amount of investment is endogenous, meaning it can be adjusted by the deciding agent. After, or ex post, the decision is taken, the investment is exogenous to the maximization problem of the agent, since it cannot be changed anymore.

4 Applications in Monetary Policy and Other Fields

In this section applications of dynamic inconsistency in different economic fields are discussed to illustrate the theoretical concept and solutions to the problem. Monetary policy is the field that has attracted by far most attention with regard to time inconsistency and also the area where theoretical considerations had most impact on politics. In addition to monetary policy, innovation policy such as patents, price regulation, capital taxation, and market power of a seller of a durable good are discussed. In all but the last case it is governmental regulation that is dynamically inconsistent. The last example illustrates that also also economic agents different than the government can behave inconsistently over time.

4.1 The Standard Model of Time Inconsistency in Monetary Policy

Kydland and Prescott (1977) have set the stage for time inconsistency by introducing a model of monetary policy. Calvo (1978), Barro and Gordon (1983), and Rogoff (1985) all have made important theoretical contributions. For the purpose of presentation, I have developed a version of this "standard model" of time inconsistency. My simplified version of the model features only three structural equations but nevertheless captures the core mechanisms.

Production

Output is determined by long-term output and unexpected inflation:

$$y_t = \bar{y}\pi_t - \pi_t^e \tag{1}$$

Economic output (GDP) in period t is denoted y_t, inflation is given by π, and the "natural level" of output is denoted $\bar{y}$. Behind this last variable stands the idea that output is growing smoothly over long time spans, mainly driven by technological change and capital accumulation (Solow 1956, Romer 1990). Long-run output is exogenous to monetary policy. Deviations from the growth path are called business cycle and here business cycles are driven only by surprise inflation. The superscript ^{e} denotes expectations, so that $\pi_t^e = \mathrm{E}\pi_t$ gives the last period's expectations for today's inflation. Why should output be a function of unexpected inflation $(\pi_t - \pi_t^e)$? In labor markets, contracts are usually signed for several years and compensation is specified in nominal wage w. Firms maximize profits with respect to labor input, so that the expected real wage $\frac{w}{1+\pi^e}$ equals the marginal product of labor in equilibrium.

If prices rise faster than expected, the marginal product of labor exceeds its cost, and firms hire more workers. With more labor input the output increases. This mechanism works as long as wage contracts are not adjusted to reflect increased prices. The whole argument builds on "nominal wage stickiness" in labor markets and is central to early Keynesian macroeconomics (Keynes 1936, Hicks 1937, Samuelson 1948). Similar arguments can be made about nominal price rigidity due to "menu costs" in good markets (Mankiw 1985)

Welfare

The second ingredient for the model is the social welfare function. The government is assumed to be benevolent and act in the interest of the society it represents. Thus the government's objective function coincides with society's preferences as expressed in the welfare function. The society likes higher output and dislikes changes in the price level:

$$\begin{aligned} W_t &= \alpha y_t^2 - \pi_t^2 \qquad (2) \\ &= \alpha(\pi_t - \pi_t^e + \bar{y})^2 - \pi_t^2 \end{aligned}$$

where α is the weight given to output maximization. In the second line (1) was substituted for y_t. Society likes higher output because it increases is consumption possibilities. On the other hand, there are many reasons to dislike both expected and unexpected inflation, including the costs of posting new prices, renegotiating wage contracts, making the tax system neutral to inflation, and increased transaction costs due to decreased holdings of cash. Fischer and Modigliani (1978) and Lucas (1994) enumerate different types of inflation costs.

Here the assumption was made that society dislikes any inflation. This is just a simplification to make the algebra simpler. In fact there are good reasons while a small, but positive rate of inflation is optimal (Camba-Mendez et al. 2003). The model results do not depend on the introduction of an optimal rate different from zero.

The government maximizes (2) with respect to π_t. In other words, monetary policy is modeled as the government directly setting the rate of price level change. There is no explicit modeling of intervening variables such as interest rates or money supply in order to keep the model simple. Because it cannot influence expectations, it treats π^e parametrically. The first order condition for a maximum can be rewritten as

$$\pi_t = \alpha(\pi_t - \pi_t^e + \bar{y})$$

Solutions

Private agents have rational expectations: On average, they predict inflation correctly. This is the third model equation:

$$\pi_t = \pi_t^e \tag{3}$$

Substitution π_t for π_t^e gives the consistent outcomes for inflation, output and the loss function:

$$\pi_t^c = \alpha\bar{y}$$
$$y_t^c = \bar{y}$$
$$W^c = \alpha(1-\alpha)y^{*2}$$

If the government could commit to some future inflation rate, it could take into account expectations credibly. Then π_t would be substituted for π_t^e *before* maximization, yielding the new welfare function

$$W_t = \alpha\bar{y} - \pi_t^2$$

Maximizing this function with respect to inflation results in the commitment solution

$$\widehat{\pi}_t = 0$$
$$\widehat{y}_t = \bar{y}$$
$$\widehat{W} = \alpha y^{*2}$$

Inflation is lower than in the consistent solution, and output is the same. Clearly, welfare is higher if commitment is feasible. Indeed, in the present model the commitment solution is first-best. The reason for this is that in this model there is no long-run trade-off between output maximization and inflation containment, because monetary policy does not have any effect on long-run output. But this solution is not feasible, because there is no way to credibly commit to future tax rates.

It is central to understand that this is *not* a government failure. At any time period, the government does *the best it can* to maximize social welfare. It does not behave irrationally, nor does it change its preferences, nor does it deviate from society's preferences. It sets a positive rate of inflation because this is the best it can do for society, given the constraints it is facing. But given its behavior is anticipated, the outcome is not first-best. To clarify this, note that the outcome would be even worse if the government set stubbornly (and irrationally) inflation to zero, given positive inflation expectations of $\pi_t^e = \pi_t^c = \alpha\bar{y}$:

$$\pi_t^s = 0$$
$$y_t^s = (1-\alpha)y^*$$
$$W^s = \alpha(1-\alpha)^2 y^{*2}$$

Even though inflation is zero, welfare is strictly lower than in the consistent solution. Given the fixed expectations $\pi_t^e = \alpha y*$, any inflation other than the consistent solution that exactly satisfies these expectations would result in lower welfare. This should be no surprise, as it follows directly from the assumptions of rational expectations. Expectations about governmental behavior are formed by expecting the government to behave rationally and welfare-maximizing. Any deviations from this solution must be welfare-reducing. In the words of Robert Barro and David Gordon (1983), "policymakers in a discretionary regime really are finding the optimal policy, subject to the applicable constraints".

This "standard model" of time inconsistency in monetary policy can be related directly to the "ingredients of time inconsistency" identified in section 3. First, the objective function depends on two arguments: the government wants both little inflation and as much output as possible. Second, these goals depend on each other: Unexpected inflation can increase current output. Third, there is stickiness: Output depends on expectations about inflation, which were formed a period earlier. Expectations cannot be reversed ex post. Fourth, the deciding agent is flexible: While expected inflation cannot be changed in the current period anymore, the monetary authorities are still able to set any level of inflation. Fifth, fully ration expectations are assumed in this model.

Also, the model does not feature uncertainty, nor change in preferences, nor a selfish government. Anyway time inconsistency leads to a sub-optimal outcome.

4.2 Independence as Solution

Now an independent central bank is introduced to the model. It is assumed that the bank is partly independent from the government, such that the resulting aggregate objective function M that determines monetary policy is the average of the central banker's utility function U^{cb} and the social welfare function W (which coincides with the governmental utility function):

$$M = \lambda U^{CB} + (1-\lambda)W \tag{4}$$

where λ is the measure of Central Bank Independence (CBI) that might depend on the constitution and laws, but also on the institutional setting, historically developed informal rules, and even the personal reputation of both high government officials and central bankers. If $\lambda = 1$, the central bank can do whatever it wants, if $\lambda = 0$ it just carries out governmental decisions.

Let's assume for the moment that both the government and the central bank have identical preferences (2). The average of two identical functions is the same function. Full independence of the central bank results in exactly the same welfare function and the same sub-optimal outcome $\pi_t = \alpha\bar{y}$ as zero independence. This is the first and highly important result with respect to central bank independence: *Independence alone does not help anything.* The value of λ is without consequence. If social, governmental, and central bank preferences coincide, independence does not have any effect.

Independence and Infinite Life

Democratic governments have necessarily limited time horizons. Incentives as well as the decision to stay in office or not are set by elections, such that democratic governments are usually forced to have a time horizon that coincide with election periods. It can be argued that independent Central Banks, in contrast, live forever. Of course, central bankers have a limited tenure in office, even though this is usually much longer than that of high government officials. In addition, even if the bank's chairman is replaced, this usually does not come with a strong break in monetary policy. Hand-overs are much more smooth than in governments. Bankers often feel responsible for past and future policy of their institution much more than policy makers, because they are generally not replaced by political opponents. For the sake of formal modeling, set us assume that governments have a limited (for example two period) time horizon and central bank have an infinite horizon. For the sake of simplicity, a perfectly independent central bank is assumed ($\lambda = 1$).

We start with the second period. For the government, the decision problem is straightforward. From the government's point of view, there is no future, so there there cannot be any reason to care about people's expectation about the future. In other words, this case resembles exactly the consistent solution of the standard model of section 4.1. In the first period, current expectations are given (they have been formed in period zero, when another government was in office). The expectations for the second period are formed in the first period, but are independent of the policy chosen in that period. Whatever the government does, people realize that the upcoming period is the last one for the government and they expect the consistent high-inflation solution. So, not being able to influence expectations, also for the first period the consistent solution is the best feasible outcome. This results does not depend on the number of periods modeled, it extends straightforward to four or eight periods. The crucial assumption is that there is a finite number of periods and thus there a last period. Backward inductions does the rest.

The central bank's problem is called an "infinite supergame" in game theory. It allows for two equilibria, which I shall call "cooperative" and "non-cooperative". The former is unstable, meaning that any deviation by any of the two players from that equilibrium will lead to the non-cooperative solution. The non-cooperative solution is stable, meaning that and deviation will lead back to the same equilibrium. However, since there is no uncertainty and no randomness in the model and I abstract from any erratic or irrational behavior, one of the two solutions will emerge and there will be no switching between the solutions or uncertainty which solution will be chosen. Will will see in a moment that the condition for the choice of the solution depends on the parameter α, the weight that society has for output maximization, and the discount rate.

The intuition is straightforward: The central bank can choose to set inflation to zero and experience welfare $\widehat{W} = \alpha y^{2*}$ today and in all periods in the future beyond the first period. Or it sets inflation to $\alpha\bar{y}$, surprising private agents and experience higher welfare $W^s = (1 + 2\alpha)\bar{y}$ once, and time-consistent welfare $W^c = \alpha(1 - \alpha)\bar{y}$ in all future periods. It can choose between a steady stream of high welfare or a jackpot plus a future stream of low welfare. Quite intuitively, if the time preference is very high, society (and the central bank) will choose the high-inflation path.

Discounted welfare over the entire future is called $\overline{W}$. In the cooperative equilibrium, discounted welfare is given by

$$\overline{W}^{coop} = \frac{1+r}{r}\alpha y^{*2} \tag{5}$$

where r is the discount rate. In the non-cooperative equilibrium, welfare is given by

$$\begin{aligned}\overline{W}^{non-coop} &= (1+2\alpha)y^{*2} + \frac{1}{r}\left(\alpha(1-\alpha)y^{*2}\right) \\ &= \left(1 + 2\alpha + \frac{1}{r}\alpha(1-\alpha)\right)\end{aligned} \tag{6}$$

The condition for a cooperative equilibrium is

$$\begin{aligned}\overline{W}^{coop} &> \overline{W}^{non-coop} \\ \frac{\alpha^2}{1+\alpha} &> r\end{aligned} \tag{7}$$

This is the second important result regarding central bank independence: *If* *governments have finite time horizons and central banks have infinite time horizons, independence can make a difference.* If CBI does increase welfare depends on the rate of time preference relative to the weight of output maximization.

Note that if the noon-cooperative solution dominates, it is not the case that $\overline{W}^{non-coop}$ emerges as a solution. Since private agents know all parameters, they anticipate the central bank is going to cheat them in the first period and they anticipate the consistent solution even then. Thus welfare is $\frac{1+r}{r}(1-\alpha)\alpha y^{*2}$, which is strictly less than the cooperative solution, for any discount rate.

Independence with a Conservative Banker

A second way CBI has been interpreted is in combination with a "conservative central banker" (Rogoff 1985). This central banker has different preferences than society by giving output stabilization less and accordingly low inflation a higher weight. This can be written as

$$U^{cb} = (\alpha - \beta)y^2 - \pi^2 \tag{8}$$

where β is the degree of "conservativeness". The higher β is the less the banker cares about output. Recall that the true social welfare function is identical with the government's preferences and was not changed. The aggregate objective function can then be written as

$$M = (\alpha - \lambda\beta)\left((\pi_t - \pi_t^e) + \bar{y}\right)^2 - \pi_t^2 \tag{9}$$

Maximizing M yields the inflation rate and welfare

$$\pi = (\alpha - \lambda\beta)\bar{y} \tag{10}$$
$$W = \alpha y^{*2} - (\alpha - \lambda\beta)\bar{y} \tag{11}$$

It is clear that welfare is maximized if $\alpha = \lambda\beta$, such that the last term in the second equation becomes zero. In this case, the first-best result is obtained. Time inconsistency is fully abrogated by the combination of inflation-avers central banker and central bank independence. It is also shown that any degree of independence is in line with a first-best outcome: The less independent the central bank is, the more conservative the central banker has to be. Of course, such a combination will quickly lead to political conflict. Furthermore, very high levels of β (higher than α) indicate that the banker actually *prefers* low output; such a person is probably hard to find. Most probably a highly independent (λ close to unity) in combination with a moderately conservative banker (β close to α) is a more feasible solution.

The German Bundesbank and the Chilean Banco Central might be good examples of such a setting. Indeed, both countries have observed exceptionally low rates of inflation despite a history of periods of very high inflation.

Independence and a Single Target

Some central banks such as the U.S. Federal Reserve (FED) seem to pursue two targets, as modeled above. Other central banks have explicitly only a single goal. The European Central Bank (ECB) is such a case. The bylaws of the bank state that "the primary objective of the ECB's monetary policy is to maintain price stability. The ECB aims at inflation rates of below, but close to, 2% over the medium term."[6] While secondary goals exist, they are fomulated in a much less specific way: "Without prejudice to the objective of price stability, the ESCB shall support the general economic policies in the Community"[7], which are "a high level of employment and sustainable and non-inflationary growth"[8].

For three reasons it makes sense to model the ECB as having only one single goal. First, there is a "primary" and several "secondary" goals. Second, while the primary goal is specified clearly in terms of a measurable outcome, all three secondary goals (employment, growth, no inflations) are formulation without any target number. Third, one of the three secondary goals is a reformulation of the primary goal ("non-inflationary" growth if the same as "price stability").

Assume a central bank has a target rate of inflation and no other goals. Bankers experience disutility when missing the target due to loss of reputation in their community or because salaries are tied to achieving the target. The bankers preferences can be specified as $U^{cb} = -(\pi_t - \pi_0)^2$, π_0 being the target rate of inflation, for example 1.9%. The policy objective function then becomes

$$M = -\lambda(\pi_t - \pi_0)^2 + (1-\lambda)\left[(\pi_t - \pi^e + \bar{y})^2 - \pi_t^2\right] \tag{12}$$

Maximizing this function with respect to π_t under rational expectations yields an inflation rate of

$$\pi_t = \lambda\pi_0 + (1-\lambda)\bar{y} \tag{13}$$

For the inflation rate to resemble the first-best solution of zero inflation, the target

[6]http://www.ecb.int/mopo/html/index.en.html
[7]http://www.ecb.int/ecb/orga/tasks/html/index.en.html
[8]Article 2 of the Treaty on European Union

rate π_0 must be set to a level that depends on the degree of independence:

$$\pi_0 = \bar{y}\frac{\lambda - 1}{\lambda} \tag{14}$$

With perfect independence, the inflation target should equal the socially warranted inflation rate, in the present model zero. With lower degrees of independence, inflation targets should be negative to yield zero inflation after struggling with the government.

Implementing the central bank an unique target can be understand as a "policy rule". Maximizing social welfare (2) is "discretionary policy, namely, the selection of that decision which is best, given the current situation" (Kydland and Prescott 1977). In contrast, targeting only inflation constraints the degrees of freedom monetary authorities have.

While being highly stylized, these three modeling exercises yield key insights. Different mechanisms can counterbalance the welfare-reducing time inconsistency in monetary policy. All of them need to be implemented in combination with an at least partly independent central bank. Independence alone, however, is not a solution to the problem.

4.3 Empirical Findings regarding CBI

From the early 1980s on economist have tried to test the "CBI hypothesis" empirically. Often it was tested econometrically if countries with more independent central banks grow faster or experience lower inflation rates than others or if a central bank reform that lead to more independence resulted in higher growth or lower inflation. The first step was to develop a quantitative measure of independence.

Measuring Independence

During the 1980s, legal independence was used as a measure. Legal aspects often include a) appointment, dismissal, and terms of office of the central bank governor, b) the way conflicts between government and central bank regarding monetary policy are resolved, c) the bank's participation in the budget process, d) the objectives of the central bank, and e) limitations on the ability of the central bank to lend to the public sector. Alesina and Summers (1993) provide a well known application of such a measure in their statistical study. Of course formalized, legal procedures do not capture all dimensions of independence.

As a consequence Cukierman et al. (1992) compiled an index of *de facto* independence. For this purpose they used the turnover rate of central bank governors as an index. They argued that turnover rates above 0.25 (indicating an average tenure of 4 years or less) indicate severe dependence from the government. In addition they looked at a) the overlap of central bank governor's tenure with that of the government, b) limitations on lending in practice, c) financial independence of the central bank's own budget, d) the function of the bank as development bank (providing subsidized credits), and others. Germany's Bundesbank scored first on Cukierman et al.'s questionair. One of their findings is that the legal measure of independence explains inflation well in OECD countries, while their measure of *de facto* independence works well in emerging economies. More recent empirical research uses both legal and effective CBI as a measure (Jacome and Vazquez 2008).

Findings of the Regression Literature

The empirical regression literature on central bank independence is vast. Berger et al. (2001) list 36 studies conducted in the second half of the 1990s alone. Google scholar reports almost a thousand economic publications on this issue since 2000 and twice that number in total.[9] Older studies often are of limited value due to technical reasons (omitted variable bias and panel data issues are widespread here) or low quality data. In their review, Berger et al. conclude that "the relationship between legal indicators of central bank independence and inflation *in OECD countries* is quite robust" (emphasize by authors). They also state that "the negative relationship between CBI and inflation is quite robust". Summarizing a 2008 special issue of the *European Journal of Political Economy* on CBI, Jakob de Haana, Donato Masciandaroc and Marc Quintynd conclude that, yes, independent central banks reduce inflation and improve welfare (Dehaan et al. 2008).

4.4 Other Economic Applications

While time inconsistency is widely studied in the context of monetary policy, most fields of economic policy are potentially prone to time inconsistency. Specifically, innovation, utility price regulation and capital income taxation are considered here. Additionally, the literature on sellers of durable goods with market power is discussed. In a path-breaking paper Coase (1972) discussed that case years before the publication of Kydland and Prescott (1977) and without using the term "inconsistency" - but in fact it is dynamic inconsistency that drives the results in his model.

[9] It was searched for ("central bank independence" empirical regression). http://scholar.google.com/scholar?num=100&hl=en&lr=&q=%22central+bank+independence%22+empirical+regression&as_ylo=2000&as_yhi=&btnG=Search&as_subj=bus

Innovation

The promotion of innovation is an often cited case of dynamic inconsistency (Gallini and Scotchmer 2002, Montgomery and Smith 2005). Innovating is costly, but once knowledge is create, it is a perfectly non-rival good, meaning that it can be used by anyone without being consumed. The marginal costs of knowledge, once generated, are zero.

After knowledge has been created, it is social optimal to use it as much as possible, thus to let anyone use it for free. But the creation of knowledge is costly. Potential innovators need to have incentives to recover their research investments. Intellectual property rights in the form of patents or copyright are a way to do this. They grant a temporary monopoly to innovators who use their monopoly rents to recover research costs. There is a clear trade-off between diffusion (which is warranted in the short run) and incentives to innovate (important in the long run).

This is where time inconsistency comes into play. It is sensible for the government to promise heavy protection (long and broad scope of patents, fierce defense of intellectual property rights) to induce inventors to invent. Once done, it is rational to lower the level of protection or stop protection at all. If this worked, society could get both: Much innovation and quick diffusion. Anticipating this reformulation of government policy, potential innovators do not invest, of course.

An example of this case is the public debate on vaccines. Many participants of the debate claim that patents on vaccines should be ignored to supply much-needed pharmaceutics to poor people. What proponents often ignore is the dynamic effect of such action on incentives on research and development. Kremer (1998) has formulated ideas how the government could commit to compensation for research while securing fast diffusion of knowledge. His mechanism is meant to reveal the true value of the innovation, such that the government can buy off the innovator and put the innovation into public domain. Due to information asymmetry between the innovator and the government, and decentralized information dispersed in the market, finding the true value is not an easy task. Kremer suggests to sell patents in public auctions where private firms can participate. In 90% of all actions the state would pay the highest bid and transfer the innovation into public domain. The remaining 10% of actions are randomly selected. In these actions, the highest bidder gets the patent and pays his bid to the innovator. This guarantees that firms bid what they believe the true value of the innovation is.

Utility Price Regulation

Time inconsistency of price regulation in markets with sunk investment costs is pretty straightforward. If for technological reasons a market faces large fixed costs, good prices need to be higher than marginal costs to recover these investment costs. Natural market power is a consequence, leading to inefficiently high prices. For social optimality, price regulation is warranted to reduce *long-term* profits to zero - as in any market with perfect competition.[10] Now take into account dynamics. Physical investment is usually "sunk", meaning that it cannot be reversed easily and at low cost. Thus the regulator can be tempted to reduce *short-term* profits to zero by setting the price equal to marginal costs. This does not allow the firms to recover their investment costs, but, if investments are already made, they will continue to operate even under serve price depression. Anticipating this regulatory behavior, utilities are reluctant to invest in the first place. This is a sub-optimal outcome due to price regulation. Because investments are not done the price regulation literature often uses the term "hold-up problem" for time inconsistency.

Note that innovation can be viewed as a similar case, where marginal costs are virtually zero, and price regulation is done indirectly by changing patent law. Abolition of patents for existing technologies is equivalent to set the price to marginal costs and short-term profits to zero.

Time inconsistency in price regulation can be related to the ingredients identified in section 3. First, the government has a double goal of inducing investments and suppressing the price of energy. Second, the government does not invest directly, but the goals depend on the decision of private utility firms. Third, sunk costs create inflexibility for firms once investment decisions are made. Fourth, the regulator is still flexible to change regulation after the investment is made. Fifths, investors anticipate the behavior of price regulators.

For several reasons, utilities are a prominent sector for this case. First, technologies like coal-fired or nuclear power plants have a specific optimal size. With today's technology, both type of power plants are run at lowest costs with a capacity of about one gigawatt electrical power (coal a little less, nuclear a little more). Reducing the capacity significantly leads to a sharp increase of costs per kWh. Capacities of one gigawatt are significant compared to the market size of an economy: A single large power plant, running 24 hours all year long can supply almost 2% of Germany's electricity demand. This results, second, in strong market concentra-

[10] Long-run profits are reduced by monopolistic competition if there is free entry to the market. If prices are regulated for political reasons, time inconsistency becomes an issue even with free entry.

tion. Most electricity markets are dominated by one (like EdF in France) to four (like EnWB, E.On, RWE, and Vattenfall in Germany) large electricity generating firms. Third, as a consequence, price regulation is widespread. I am not aware of any OECD country where electricity prices are not regulated. The same is true for most emerging economies. Finally, investments are often almost irreversible. Power generating technology is highly specific: You can use a power plant for producing electricity, but nothing else. In addition, large part of investment consist of building investments, rendering selling a plant to other countries prohibetively expensive: While even used steel mills are shipped internationally, this has never happened with a power plant. What has been said for the power sector is also true for fresh water supply, wastewater disposal, gas, railroad-based public transportation, and other utilities. It is less true, however, for solid waste disposal.

Levine et al. (2005) have thoroughly modeled time inconsistency of price regulation in the utility market. Due to space constraints I abstain from presenting formalisms and report only the central findings. The authors find that discretionary price regulation of utility firms to result in higher prices that under commitment to a certain price level. They also argue that commitment is harder than in monetary policy because the "temptation period" is much longer: Energy investments last decades while the labor market is sticky for months or few years, thus price regulators have more time to extract profits from investors. The authors also conclude that the temptation to deviate from a committed price is larger the lower the depreciation rate, the lower exogenous demand growth, and the lower the rate of time preference is. If the depreciation rate is lower, plants can be used for a longer time (the temptation period is longer). If demand grows slowly, currently existing machinery can satisfy demand for a long time and no new investments are necessary. They conclude that just like a "conservative central banker" a "pro-industry regulator" could result in a Pareto improvement.

Capital Income Taxation

As Stanley Fischer (1980) noted, time inconsistency is also a serious issue in tax policy. Taxing labor is distortionary, thus welfare-reducing, since household's leisure-work decision is distorted. Taxing capital income, by contrast, is non-distortionary in the short term, since capital investment are sunk; there is no decision that could be distorted. In the long run of course things look very different. Just as the choice between leisure and work the decision between investing and consuming is endogenous.

As a result, in the Fischer (1980) model the government can increase welfare by reducing labor taxes and increase capital taxes. Anticipating this, households save too little, fearing heavy taxation once investments are made. At the heart of the problem lies the irreversibility of investments. Taxing capital is in the model just a way to extract the returns on investment from the investor, exactly like price regulation or weakening of intellectual property rights. Similar arguments could be made for human capital investments.

Selling vs. Leasing

One of the most interesting, and often overlooked, works in the time inconsistency literature is a short article by Ronald Coase published in 1972, five years before Kydland and Prescott introduced the term "time inconsistency" to economic theory. Titled "Durability and Monopoly", Coase models a monopolist that sells a durable good, showing that time inconsistency is not only an issue for policy, but potentially for any economic agent with strategic power.

Coase takes the illustrative example of a monopolist that sells land, an entirely durable good. Standard static economics would lead to the conclusion that maximizing profits, the monopolist would sell only part of the land, holding some back to increase the price.

But dynamics change the picture. Once the profit-maximizing amount of land is sold, the monopolist finds it profitable to sell another portion of land, since he gets additional revenues at zero costs. Once this is done he sells a third portion, and so on. Anticipating this stepwise selling no potential buyer would pay more than the discounted marginal productivity of land: Competition between the monopolist today and himself in the future perfectly resembles competition between different contemporaneous suppliers of land. Note that here time inconsistency, while reducing the monopolist's profit, increases welfare.

Reflecting his (1960) seminal article on external effects, Coase discusses several private solutions and contract arrangements that allow the monopolist to capture at least some rents. First, the monopolist could bind himself legally to hold a proportion of land back throughout the future, or buy back any land at a pre-specified price. Today such a contract would be called commitment device, something that is feasible for private agents operating under the rule of law, but much less for sovereign countries setting the law themselves. Second, the monopolist could lease the land for short time periods. As in the case of monetary policy in section 4.2, in a game with infinite periods the monopolist refrains from leasing more land and a cooperative equilibrium is feasible. Third, the landowner might give the land hold back to someone who is less concerned about money-making: he could donate it to the government in order to establish National Parks on it. This today would be called delegation. Finally, the producer could modify the technology of the good itself. This is not possible in the case of land, but it is feasible for manufactured and other durables. The producer can simply make them less durable.

Bulow (1982) models the Coasian setting formally. In a two-period setting he shows that the market power of a durable good monopolists is decreased because the sale of their products creates a second-hand market that is not controlled by the producer. He also shows formally that the monopolist might increase its rents through planned obsolescence (making the good less durable).

5 Time Inconsistency of Climate Policy: Literature Review

While there is a vast theoretical and empirical literature on dynamic inconsistency in monetary policy and a significant literature on tax policy, this is much less true for other policies. In environmental policy, I have identified three important articles on time inconsistency.

Marsiliani and Renström (2000) develop a median voter model where the poor-skilled majority taxes energy heavily for distributional purposes. Helm et al. (2004) present a model where the carbon tax is distortionary. In both models the persistent variable is investment in energy efficiency. In both models time inconsistency causes an upward bias, leading to too much investment and too much mitigation. In both models, taxes are increased ex post for revenue purposes. The main difference between the models is the purpose for revenue generation: In Marsiliani and Renström (2000) it is used for redistribution, in Helm et al. (2004) it is used to finance public goods.

Baldursson and von der Fehr (2008) develop a very different model. They compare a tax regime to a cap and trade system in terms of revenue generation under time inconsistency. The persistent variable are emission permits hold by private firms. The cap and trade system leads to time inconsistent policy because the government is induced to sell more and more permits, just as a monopolist is induced to sell more and more of a durable good. This resembles Coase's (1972) model. A tax regime does not face this problem.

A three models rely heavily on public finance arguments. In all three models time inconsistency arises because government wants to rise revenues, although for different purposes and through different channels. In economic theory, this is expressed by assuming the marginal cost of public funds (MCF) to be above unity. I think there are several reasons to believe this is not true. The discussion on the MCF is postponed to section 6.1.

These three models are discussed in some detail in turn. Finally, the rest of the time inconsistency literature in environmental economics is reviewed quickly.

5.1 Redistribution: Marsiliani & Renström (2000)

Laura Marsiliani and Thomas Renström (2000) present a model where the poor majority aims to redistribute income from richer households via surprise energy taxation. Time inconsistency arises because after energy efficiency investments are made, quantities react slower to taxes than before. This makes taxation more effective and more attractive.

The Theory of Taxation

To understand the intuition of the model some comments on tax theory might be warranted. A formal description is postponed to section 6.1.

Assume government wants to raise revenues by taxing a good. Increasing the tax rate has two effects on government revenue. It increases revenues for a given amount of goods sold. This is called the “price effect”. But increasing the tax also increases the price and dampens the demand for the good, since consumers substitute or decrease consumption. A smaller quantity sold means lower tax revenues. This is the “quantity effect”. The quantity effect counteracts the price effect and at at very high rates outweights the price effect. At this point a further tax increase *decreases* tax revenues. The range of taxes beyond this rate is called “inefficient taxation” or “overtaxation”.

If the elasticity of demand is larger than unity in absolute terms, a good is overtaxed. To maximize tax revenues, taxes should be increased up to this point. Here price and quantity effects just cancel out. The reason for time inconsistency in the Marsiliani-Renström model and the Helm et al. model is that after investments are made, the quantity effect is smaller. Consequently, it is more beneficial to rise the tax rate than before. The optimal tax rate is larger ex post than ex ante.

The Marsiliani-Renström model

Marsilian and Renström model households’ efficiency investments over two periods. In the first periods, households invest in efficiency; for example they decide to buy a fuel-efficient car (or not) or build a zero-energy house (or not). Energy consumption causes a negative externality on society, such as damages from climate change. Government can tax labor and energy, for both revenue purposes and to internalize the negative external effects of energy consumption. Taxes as well as labor supply can be adjusted in the second period while investment are irreversible. Consequently in the second period energy consumption is less elastic than labor supply, and energy is “overtaxed”.

Two types of households are modeled, with low and high labor productivity (“poor” and “rich”). They have an exogenously given budget in the first period, which they use for consumption and investment in energy efficiency. Because high skilled households expect to receive a high income in the second period, they want to consume much in both periods to smooth intertemporal consumption. Accordingly they invest little of their limited budget in energy efficiency in order to finance first period consumption. As a consequence, high skilled households consume more energy in the second period, not only absolutely but also relatively to low skilled households. This is where politics come into play.

The political system is modeled in a median voter manner. Because low skilled households are in majority, they determine policy. They use both labor taxation and energy taxation to redistribute consumption. Why is it not optimal to tax only labor? With higher tax rates, high skilled workers reduce their labor supply, leading to lower tax revenues. As energy efficiency investments are sunk in the second period, energy consumption responds weaker (less elastic) to high tax rates. Since the rich consume proportionally more energy, energy taxes are progressive. Taxing energy and redistribute revenues is sensible for the majority.

While in most examples in section 4.4 time inconsistency lead to underinvestment, here the opposite is the case. High skilled households expect to be taxed heavily via energy consumption and hence invest *more* than the optimal amount in efficiency. If the low skilled majority could commit to some tax level, energy taxes as well as efficiency investments would be lower and emissions higher. Time inconsistency causes an upward bias on energy taxes. Due to time inconsistency too much environmental protection is done.

Flaws in the model

I am convinced that all model mechanics are worked out well by the authors. However, I do believe that their assumptions are flawed in a way that turn the results upside down. A crucial, and I believe incorrect, assumption is that there is no credit market. Rich households invest less in efficiency during period one because they want to consume. However, a straightforward solution for them would be to invest in energy efficiency on credit and repay in period two. In other words, the crucial flaw is to assume budgets to be intertemporally impermeable.

Allowing for borrowing and lending would probably result in underproportional energy consumption by rich households. Consequently, the low skilled majority had an incentive to *lower* energy taxes in the second period (since they are hit harder themselves than the rich by energy taxes). Because rich households would anticipate, time inconsistency would result in a downward bias on energy taxes and cause underinvestment in efficiency.

Indeed, empirics seem to support that notion. Symons et al. (2000) found in an empirical investigation that energy taxes are regressive in all but one European country. Helm et al. (2004) state that energy taxes are “viewed as being highly regressive”.

Still, the contribution of the authors is very substantial. Fundamentally, they have developed a model that explains why the government has an incentive to change taxes after investments are sunk: To redistribute income. If irreversible investments are made to different degrees by rich an poor, they are good targets for redistributive income, and they are potentially prone to time inconsistency.

Tax earmarking as a solution?

Marsiliani and Renström also present an innovative idea how to thwart dynamic inconsistency. They propose to "earmark" taxes, that is to dedicate specific taxes to finance specific public services. For example, the German "Öko-Steuer" on fuel and electricity is earmarked to contribute to social insurance only. Earmarking taxes reduces the freedom of parliament to determine the governmental budget. Here it serves as an (imperfect) commitment device.

Recall that in the model too much GHG is abated and energy is taxed too heavily. Now if energy taxes are earmarked to abatement and earmarked taxes imply that inefficiently much abatement is done, the majority has an incentive to lower energy taxes. By designing the budget in a "wrong" way and linking specific taxes to specific expenditures, the voters have an incentive to reduce that wrong expenditure by reducing the linked tax - and that is what is wanted.

Here, I believe, the model fails to represent reality is a sufficient accurate way. They describe the policy process as a game between government (who earmarks taxes) and voters (who decide on the tax rate). It is not clear at all, why the government should be able to earmark taxes, but not change their rates - or why voters should not be able to change earmarking rules. Furthermore, both processes, earmarking and setting tax rates, are both done by government officials, deputies, and political parties. Both processes are not two distinct processes done by different agents, but two integral and dependent parts of tax regulation conducted by a single set of agents.

To sum up, while the model indicates an important way through which time inconsistency works, I think it fails to present a realistic solution to the problem.

Abrego & Perroni (2002)

Abrego and Perroni (2002) develop a similar model where time inconsistency arises because heterogeneous agents invest differently in efficiency and the poor majority taxes for redistribution. In their model, the differences in investment do not stem from liquidity constraints during the first period, but from different preferences for the polluting good. As a solution, they do not propose tax earmarking, but research subsidies. Research subsidies can be seen as an imperfect, but less time inconsistent substitute for carbon taxation. They are discussed in more detail in section 7.3.

5.2 Distortionary Taxes: Helm et al. (2003)

Dieter Helm, Cameron Hepburn, and Richard Mash from Oxford University developed a model of distortionary as well as revenue-generating climate policy (2003, 2004). Not redistribution, but the social value of government revenues is the driving force behind energy taxation. While the 2003 article discusses the issue verbally, the 2004 working paper presents the formal model.

The Helm et al. model

Since I regard the model as the most relevant on the issue, it is presented here formally, albeit in a somewhat simplified form. Energy consumption Q depends on energy price P and exhibits constant elasticity of demand:

$$Q = \alpha P^{-\epsilon} \tag{15}$$

GHG Emissions E are linear in energy, depending on the transformation technology e:

$$E = eQ \tag{16}$$

where e are the specific (per unit) emissions. Without loss of generality, α is set to unity to simplify the presentation..

Firms' profits are zero due to Cournot competition with free entry. Government can tax energy with an ad valorem carbon tax t on emissions E, leading to a after-tax average per unit price $P = P_0 + et$. Taxes are fully shifted forward such that $\partial P/\partial t = e$. For a particular technology energy efficiency is fixed $\bar{e}$, but if the technology choice is endogenized it depends on the tax rate (higher taxes induce firms to apply a more efficient technology with smaller specific emissions e):

$$E(e,t) = \bar{e}Q = \bar{e}P^{-\epsilon} = \bar{e}^{1-\epsilon}t^{-\epsilon} \tag{17}$$

$$E(t) = e(t)^{1-\epsilon}t^{-\epsilon} \tag{18}$$

Welfare depends on Consumer Surplus (CS) s, tax revenue $r = tE$ and disutility from pollution $-\lambda E^{\gamma}$.

$$W = s + vr - \lambda E^{-\gamma} \tag{19}$$

CS, the "profit" households receive from consumption, is decreased by taxation as the energy price rise and the quantity consumed decreases. For isoelastic demand CS can be written as

$$s = \frac{1}{1-\epsilon}(P_0^{1-\epsilon} - P(t)^{1-\epsilon}) \tag{20}$$

Tax revenue is valued according to the so called MCF v. This variable determines if resources are valued more if they are hold by government or of they are hold by households (discussed in more detail in subsection 6.1). The parameter λ indicates how society values climate change against consumption losses. The welfare function is specified in units of consumer surplus. The government is benevolent and maximizes social welfare.

If the government cannot commit to a certain tax level, it takes $e = \bar{e}$ as given. It maximizes welfare with respect to taxes, taking only the direct effect through prices into account:

$$\frac{\partial W}{\partial t} = \frac{\partial s}{\partial t} + v\frac{\partial r}{\partial t} - \lambda\frac{\partial E}{\partial t} \tag{21}$$

The optimal tax rate is the one for that $\frac{\partial W}{\partial t} = 0$.

If commitment is possible, the government takes the indirect effect via technology into account. Firms can invest in more efficient technology, yielding more energy output per ton of emissions. The higher the tax, the more they will invest: $de/dt < 0$:

$$\begin{aligned} \frac{dW}{dt} &= \frac{\partial W}{\partial t} + \frac{\partial W}{\partial e}\frac{de}{dt} \\ &= \frac{\partial s}{\partial t} + v\frac{\partial r}{\partial t} - \lambda\frac{\partial E}{\partial t} + \left(\frac{\partial s}{\partial e} + v\frac{\partial r}{\partial e} - \lambda\frac{\partial E}{\partial e}\right)\frac{de}{dt} \end{aligned} \tag{22}$$

The authors claim that the marginal effects of tax changes under commitment can be expressed like this:

$$\frac{dW}{dt} = \left(1 - \frac{P}{e^2\epsilon}\frac{de}{dt}\right)\frac{\partial W}{\partial t} - (1-v)\frac{P^{1-\epsilon}\alpha}{e\epsilon}\frac{de}{dt} \tag{23}$$

Note that if $v = 1$, the second term drops out. If $\frac{dW}{dt} = 0$, then also $\frac{\partial W}{\partial t} = 0$, thus both optimal tax rates coincide. Only if $v \neq 1$ the consistent solution deviates from the commitment solution. In the Helm et al. model *only the marginal costs of finance drives time consistency.* If $v > 1$, a plausible assumption, the government has an incentive to increase taxes ex post in order to increase tax revenues: Time inconsistency causes an upward bias on the carbon tax. Anticipating, firms overinvest in efficiency and there is too much GHG abatement.

Differences to Marsiliani & Renström (2001)

The model is similar to Marsiliani and Renström (2000). If taxes are increased before choosing technology, firms can evade taxation by switching to more efficient equipment. Tax increases are less effective under commitment in terms of revenue generation, because higher taxes do not only decrease demand, but also increase efficiency.

In the case of Marsiliani and Renström the reason for increased taxation was redistribution demanded by a low-income majority. Here the reason is that revenues are valued highly due to high MCF.

Flaws in the model

The central result of Helm at al. is that only the marginal cost of finance drive time consistency. I disagree. Time consistency arises because any of the three components of welfare (revenues, consumer surplus, and emissions) react differently to tax increases after investments are sunk. I show below in section 6 that indeed in general all three react different ex ante and ex post.

According to this model, only revenues seems to react differently. It is not clear to me, neither intuitively nor formally, why this is the case. In the appendix the authors argue that due to the Envelope Theorem, tax increases before and after the investment decision have the same effects on consumer surplus. But if firms can invest in technology, the specific emissions are lowered and accordingly the price increase of final energy due to carbon taxation is weakened. An email to the authors addressing my doubts was not replied.

5.3 Prices vs. Quantities: Baldursson & von der Fehr (2008)

Economist often disregard “command and control” regulation of external effects such as emissions as being socially costly. Instead, they recommend incentive-driven regulation that equalizes marginal costs of mitigation across abatement options. Within this family of “market-friendly” regulatory instruments, two policies are often compared: Taxes, and cap and trade systems. In the former case the state charges polluters with a certain fee for every ton of GHG emissions. In the latter the government issues a certain amount of permits that give the right to emit one ton of GHG, and economic agents are allowed to trade these permits freely.

The prices vs. quantities debate

This debate lasts for almost 40 years within environmental economics and is usually entitled “prices vs. quantities”. Taxes set directly the price of a ton of CO_2 (and the total quantity of emission is determined by the market). Quota systems determine the total amount of pollution (and the price of a ton of CP_2 is determined by the market). In the recent policy debate in the U.S. “prices vs. quantities” has been called “taxes vs. trade”. Emission permits are also called “allowances” or “certificates”.

Montgomery (1972) has shown formally that with the appropriate tax rate and total cap the outcome under both regimes is identical: Total emissions, the unit price of emissions, and total (social) abatement costs are the same. If permits are sold (auctioned), government revenue is also the same in both regimes.

This holds for a static setting without uncertainty. Weitzman (1974) showed in a path-breaking article that both instruments are not equivalent if there is uncertainty about mitigation costs. If abatement turns out to be much more costly than expected, in a tax system the total amount of emissions increase, while the costs of emissions remain the same. In a cap and trade regime the total amount is fixed, such that total emissions remain the same while the permit price increases.

Society might be avers against a cost overshoot or an emission overshoot. For example, if tipping points in the climate system exist (see section 2), damages become dramatic at certain points and society dislikes heavily to exceed this point. Emission overshoot is very costly compared to price overshoot. A cap and trade system is better than an emission tax.

Weitzman showed formally that, depending on the relative slope of the marginal cost curve and the marginal damage curve, a price or a quantity regime is the better choice. A very steeply rising marginal damage curve corresponds to the tipping point scenario in climate policy. In contrast, a steeply falling marginal cost curve would make a price system dominate a quota regime.

The Baldursson-von der Fehr model

Fridrik Baldursson and Nils-Henrik von der Fehr (2008) discuss the case of time inconsistency in the context of policy instrument choice between price and quantity regulation. Besides internalizing the climate externality, government also wants to rise revenues. The MCF is above unity. Their argument is very similar to the monopolist of a durable good discussed by Coase (1972). Indeed, their formal model draws directly on Bulow (1982) who formalizes the Coase model (see section 4.4).

Here, the revenue-raising government corresponds to the monopolist, emission permits are the durable good, taxation corresponds to leasing, and shortening the duration period of allowances corresponds to planned obsolescence.

The intuition goes as follows. The government sets the optimal tax rate, weighting damages of emissions against costs of abatement. It also wants to increase revenues. A higher tax rate increases revenues, but also decreases the tax base since polluters abate emissions. The more elastic emissions, the lower the optimal tax rate will be. Now take the case of permits. The government auctions the socially optimal number of permits for two periods at the begin of the first period. At the begin of the second period it can choose to sell additional permits. It will indeed be optimal to sell additional allowance, since the tax base responds less elastically, the reason being the permits already hold by the firms. In other words, by depressing the permit price the government can partially expropriate firms' assets. Because the optimal number of permits changes over time, policy is time inconsistent. Anticipating the supply of additional permits, firms value them less. With a lower permit price there will be less mitigation effort and too many emissions - a socially sub-optimal outcome.

Baldursson and von der Fehr show that price and quantity regulation are not equivalent in a dynamic setting - even if there is no uncertainty at all. In the other two models discussed in detail, time inconsistency arose because the tax base responds less elastically after fixed investments are made by firms. Here the tax base responds less elastically because emissions permits are hold by firms. While there is no obvious response to the sunk investment dilemma, the problem of permit holdings can be alleviated easily by shortening the time permits are hold to decrease the number of permits banked across periods. If no assets are hold, there cannot be any expropriation.

The Limited Scope of Banking

Dynamic inconsistency arise in the model because private agents hold permits at the end of the period. Period length is determined by the frequency with which the government can adjust regulatory policy. In the case of the EU ETS, the number of permits is determined for seven years (2013-20). The incentive to expand permit allocation beyond the efficient level stems from the number of allowances banked by private actors at the end of 2020.

If, for example, 10% of one years emissions are banked, and the post-2020 trading phase also lasts seven years, the permit stock banked represent a merely 1.4% of all emissions sold. This is by any means a too small amount to have any impact on policy. Time inconsistency arises because the government expropriates the owners of banked permits. If there are only few permits banked, the incentive to change policy is very low.

While being an enlightening theoretical contribution, I don't believe the mechanism identified by Baldursson and von der Fehr has a significant impact on actual policy formation.

Biglaiser et al. (1995)

Biglaiser et al. (1995) use a similar argument in favor of environmental taxes over permit markets. They assume permits live forever, that is, a permit allows the emission of one ton of CO_2 every year again. Then firms have an incentive to drive up the permit price because this increases the value of their asset portfolio of allowances. If firms have market power on the permit market, as Biglaiser et al. assume, then they can strategically underinvest in abatement technology, drive up permit prices and increase the book value of their assets.

Empirically, very few permit markets operate with such infinitely living permits-as-assets, and at least on CO_2 markets market power is highly limited: The European trading scheme has more than 12.000 participants - something very close to perfect markets. Because of the limited scope of banking and the limited market power on the permit market, the mechanism identified by Biglaiser et al. is likely to be insignificant in practice.

5.4 More Literature

In this subsection another five articles are discussed very shorty. I am confident that these are virtually all economic publications that discuss time inconsistency in environmental policy. Some others claim to discuss time inconsistency, but seem to confuse issues. For example, although entitling their article "Time inconsistency", D'artigues et al. (2007) merely discuss irrational government regulation in a two-period model.

Ismer and Neuhoff (2009)

Ismer and Neuhoff (2009) make the very well-taken point that time inconsistency arises not only with respect to private investors, but also with respect to foreign governments in the context of multilateral climate policy. They argue that such "external commitment problems" can induce free-riding if foreign emissions cannot be observed quickly. However, rational agent theory has very little to say why governments accept such international agreements at all. In addition, monitoring of national emissions is well established under the UNFCCC. As a consequence, this argument might not be too relevant after all.

They propose a solution to time inconsistency, too. They suggest that a floor (minimum) permit price could be implemented through emitting put options. Owners of such options can, but don't have to, sell their permits at a certain date for a certain "strike" price back to the government. I will come back to this proposal when talking about commitment devices in section 7.

Abrego and Perroni (2002)

Similar to Marsiliani and Renström, Abrego and Perroni (2002) model the trade-off between environmental efficiency and distributive objectives in the context of fixed investment, e.g. in innovation. They propose to partially substitute climate policy with research or investment subsidies. Such subsidies are paid immediately, thus do not suffer from time inconsistency. However, they come at the cost of being less efficient since equalizing marginal abatement costs across technologies is generally not feasible given the informational constraints of research subsidies. Some subsidies will be captured by inefficient technologies, but combating time inconsistency might be worth it. In other words, Abrego and Perroni propose research subsidies as an alternative, less time inconsistent, policy to carbon taxation or a cap and trade system.

Laffont and Tirole (1996) and Montgomery and Smith (2005)

Laffont and Tirole (1996), who have worked much on innovation and intellectual property rights, discuss a cap and trade system with technological innovation. They argue, similar to reducing patent protection after innovations are made, issuing additional emission permits is a way to transfer private innovation rents to the state. Because agents anticipate, they underinvest in technology even if there is a reliable patent system in place. One should add that this is also true for an emission tax, thus the model does not affect the prices vs. quantities debate. It is easy to generalize their argument that in any market with governmental price regulation innovation rents might be captured by the state through lowering the price. Montgomery and Smith (2005) use the same line of argument to support R&D subsidies for low-carbon technologies.

In normal markets created by private demand, an existing system of intellectual property rights is sufficient to give innovators a substantial part of innovation rents. But carbon markets are different. They are *created* by governmental policy itself.

Thus any change in regulation also affects innovators who recover their research and development costs by drawing on rents of these markets. Thus in climate policy, governments have a second instrument at hand to expropriate innovators: To lower the price of carbon. Just as patents, carbon taxation is prone to time inconsistency since it can be used to expropriate innovators once innovations are made.

Kennedy and Lapante (2000)

In their short paper, Kennedy and Laplante (2000) note that climate policy induces cost-reducing innovation and that changes the optimal tax rate. They model result, however, is an artifact of assuming discrete technology. With continuous technology, no time inconsistency arises.

6 A Model of Time Inconsistency of Climate Policy

This sections presents a new stylized model of the final energy (e.g. electricity) market under carbon taxation. The aim is to identify the parameters that determine time inconsistency in climate policy. Specifically, I am interested in two questions. a) Under which conditions is climate policy dynamically inconsistent? And what is the "direction of time inconsistency" - is the consistent policy softer or tighter than under commitment?

The model specifies electricity production as a function of fossil fuels and capital. The capital stock is persistent and cannot be changed quickly. Climate policy is modeled as a carbon tax or a cap and trade system (and not, e.g., command and control measures, feed-in tariffs, or research subsidies). It takes into account damages from climate change, distortionary taxation, marginal costs of public finance different from unity, increasing marginal costs of production, and sunk capital investments. There is no market power, no technological progress, and no uncertainty in the model. The regulator is benevolent and maximizes a constant welfare function. Households are not modeled explicitly, such that distributional issues play no role. The model generalizes Helm et al. (2004), but comes to fundamentally different conclusions.

These are the central results of the model:

1. Taking public finance aspects into account, the optimal carbon tax is larger than the marginal damages from climate change.

2. If, and only if, investment decisions in fixed capital are influenced by carbon taxation, time inconsistency arises.

3. If investments respond positively on carbon taxation, and public finance plays little role, time inconsistency causes a downward bias on carbon taxes.

4. Under a Cobb-Douglas specification, investments respond positively on carbon taxes if, and only if, the price elasticity of demand is smaller than unity in absolute value, which seems to be the case empirically.

5. Due to the downward bias of the tax, final energy consumption is too high compared to the welfare optimum, emissions are too high, and investment is too low.

6.1 Welfare and the Optimal Carbon Tax Rate

Welfare Function

Policy is made by a benevolent planer or government with perfect foresight who maximizes social welfare. The welfare function W is an expression of the true preferences of society and depends linearly on consumer surplus S, government revenues R, and greenhouse gas emissions E:

$$W = S + vR - \lambda E \tag{24}$$

where v represents the marginal cost of public funds (MCF) and λ is a weight parameter that expresses the marginal damages from climate change due to GHG emissions.[11] Welfare is expressed in units of consumer surplus.

The three components of the welfare function capture the distortionary effects of taxation, the wish to generate revenues, and the wish to internalize the climate externality. The government's desire to increase revenues is an important mechanism for time inconsistency in the tax and investment literature (see section 4.4).

The government maximizes welfare with respect to the carbon tax t, the only policy instrument. The optimal tax rate t^* is the one for that the first order condition is fulfilled

$$\frac{dW}{dt} = \frac{dS}{dt} + v\frac{dR}{dt} - \lambda\frac{dE}{dt} \stackrel{!}{=} 0 \tag{25}$$

If any of the three derivatives changes over time, policy is inconsistent. As will be shown in a moment, in general all three derivatives will change over time.

The Marginal Cost of Finance and Double Dividends

The marginal cost of public funds (MCF) v is the economic cost of raising an additional Euro of tax revenue. Typically, the MCF is assumed to be above unity. This means that one Euro in government's budget is valued higher than one Euro in households' budgets. Why is this the case? All taxation is generally distortionary and causes dead weight loss. Thus taxation is *not* only a cash transfer from households to the government. For example, a value added tax distorts the consumption decision between market and non-market goods, such as leisure.

[11] The assumption of constant marginal damages is very strong. The climate system is highly complex and features many feedback effects, leading to non-linearities and discontinuities. In addition, the present formulation does not take into account that damages from climate change are a stock externality rather than a flow externality. Nordhaus and Boyer (2000), however, argue that damages depend exponentially from temperature change and temperature change depends logarithmically on emissions. As a consequence, damages are roughly linear in emissions.

Receiving one Euro of additional carbon tax revenue allows the government to lower other taxes by one Euro, for example the value added tax. This reduction decreases the economic tax burden for households by *more* than one Euro (v Euros) because it reduced distortions and the dead weight loss. If costless lump-sum taxation was feasible, the MCF would be unity (Pigou 1928, Harberger 1964).

If taxation is costly (and not only a transfer from household to government budget), why does it exist at all? The reason is that government has to finance public goods. Public goods cannot be provided through markets since it is non-excludable. Classical examples include defense, law enforcement (including the system of property rights), and many environmental goods. Since these public goods are valued much by households, the marginal benefit of government expenditures is larger than unity, too. At the optimal size of government budget the marginal costs of public finance coincide with the marginal benefits of public expenditures.

Consequently, there is another interpretation of v. Instead of being the marginal costs of public finance, it could also be called the “marginal benefit of public expenditure”: With one Euro of additional revenue from the carbon tax, the government can spend one additional Euro on the supply of public goods and increase households’ economic welfare by *more* than one Euro (v Euros). At the optimal level of governmental spending, the marginal cost of finance and the marginal benefit of expenditure are identical and both interpretations are equally valid.

The possibility to decrease the welfare-reducing tax burden as well as welfare-reducing externalities at the same time through environmental taxation is sometimes called the “double dividend” of environmental taxes (Goulder et al. 1999, Goulder 1995, Bovenberg and de Mooij 1994).

In their seminal article on “the theory of the second best”, Lipsey and Lancaster (1956) have demonstrated that distortions such as taxes can be welfare-increasing if the economy is already distorted by, for example, monopolies, externalities, public goods, or other taxes. The intuition behind this argument is that introducing another distortion might actually counterbalance existing distortions. This means that the MCF can also be smaller than unity (Stiglitz and Dasgupta 1971, Atkinson and Stern 1974). It does also mean that there is not “the” MCF, but any revenue-raising distortionary policy instrument has a specific value of v. As Helm et al. (2004) argue, the MCF for carbon taxation are probably “slightly above unity”, although robust econometric evidence is missing.

Tax Theorie: Revenues and Internalization

This subsection is a quick refresher of the economic theory of taxation. Taxes are seen as instrument for the triple purpose of revenue generation, internalization of external effects, and maximizing of economic surplus. Only taxes on a specific good (not an VAT or an income tax) in a partial equilibrium framework are analyzed.

Tax theory is introduced in three steps. Each step represents a different governmental objective function. First, consider a government that simply wants to maximize its own revenues

$$R = q(t) \cdot t \tag{26}$$

where q is the quantity of a good and t is the tax rate on that good. Maximization yields the optimal tax rate

$$t_R^* = -\frac{q}{\frac{\partial q}{\partial t}} \tag{27}$$

Since demand declines due to higher taxes, the optimal tax is smaller than infinity. The revenue-maximizing tax rate can be also expressed in terms of the elasticity of demand with respect to taxation:

$$-\epsilon_{q,t} = 1 \tag{28}$$

where $\epsilon_{q,t} = \frac{\partial q}{\partial t}\frac{t}{q}$ is the elasticity of demand with respect to taxation. To maximize revenues, government should increase taxes up to the point where the elasticity equals unity in absolute value. The optimal tax rate is equivalent to the profit maximizing price for a monopolistic firm.[12]

Second, consider a government that takes into account the effect of taxation on the economic welfare of consumers and producers. The objective function is

$$w = S + vR \tag{29}$$

where S is the economic surplus and v is the marginal cost of finance. Surplus is the sum of producer surplus and consumer surplus. This is the integral under the inverse demand curve minus the integral of the marginal cost curve minus transfers to the government.

Accordingly,

$$w = \int_0^q p(q)dq - \int_0^q c(q)dq - qt + vqt \tag{30}$$

[12]The elasticity $\epsilon_{q,t}$ is equivalent to the demand elasticity $\eta = \frac{\partial q}{\partial p}\frac{p}{q}$ if and only if taxes are fully shifted forward to consumers.

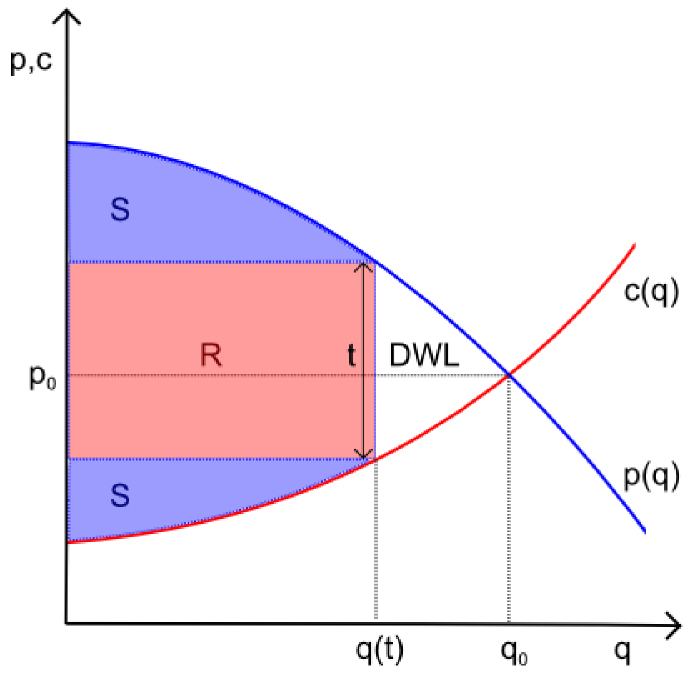

Figure 2: Consumer surplus, producer surplus, tax revenue, and dead weight loss in an one-good partial equilibrium framework.

where c are marginal costs of producing q. Taking into account that $p - c = t$, maximization with respect to t yields the optimal tax rate

$$t_w^* = -\frac{q}{\frac{\partial q}{\partial t}} \frac{v-1}{v} \tag{31}$$

For $v = 1$ the optimal tax rate is zero. This is a standard result in welfare economics. If there is no need for public finance, then there should be no taxation, because taxation is distorting. If $v > 1$, e.g. because public goods need to be financed and alternative sources of finance are distortionary, the optimal tax rate is positive and increasing in v: If there is need for public finance, indeed there should be taxation of good q. If $v < 1$ (money is wasted by the government), then the optimal tax rate is negative (a subsidy). For $v \to \infty$, the optimal tax rate is the revenue-maximizing rate t_R^*.

Third, look at the case where the production or the consumption of the good q causes a negative externality λ on society. Governments wants to internalize the external effect and maximizes social welfare

$$W = S + vR - \lambda q \tag{32}$$

where $\lambda > 0$ is the marginal damage the good does to society. Maximization yields the optimal tax rate

$$t_W^* = -\frac{q}{\frac{\partial q}{\partial t}}\frac{v-1}{v} + \frac{\lambda}{v} \tag{33}$$

For $v = 1$, the optimal tax rate is the Pigouvian rate λ that equals the marginal damage (Pigou 1928). Higher values of v imply a higher optimal rate and lower values a lower rate. This is an important insight: If public finance is taken into account, the optimal tax rate is generally different from the Pigouvian rate. For $v \to \infty$, the externality plays no role and the optimal rate becomes the revenues-maximizing rate t_R^*. A similar welfare function will be used in the following.

Optimal Carbon Taxation

This is a model of carbon taxation and the final energy (e.g. electricity) market. Economic surplus is generated by the *output* (electricity) while the negative externality is caused by an *input* (fossil fuels, or carbon). Revenues are generated by taxing the input. Because a two-good model is needed, the analysis becomes slightly more complicated.

The government maximizes social welfare with respect to a single instrument, the carbon tax t (there is no electricity tax). In a cap and trade system t represents the implicit permit price per ton of CO_2. In this model a cap and trade system is equivalent to a tax, thus the model does not contribute anything to the "prices vs. quantities" debate. All results hold for a price regime as well as a quantity regime. Electricity demand is denoted $q(t)$, tax revenue R, and economic surplus S. Electricity price is p and the marginal costs of production are c. Emissions are denoted E and cause a marginal damage of λ on society.

The government maximizes welfare

$$W = S + vR - \lambda E \tag{34}$$

$$= \int_0^q p(q)dq - \int_0^q c(q)dq - Et + vEt - \lambda E \tag{35}$$

Note that surplus is the area between the inverse demand curve and the marginal cost curve (both a function of q) and the transfer to the government (a function of E). Maximization with respect to t gives the first order condition

$$\frac{dW}{dt} = (p-c)\frac{dq}{dt} + (v-1)(E + \frac{dE}{dt}) - \lambda\frac{dE}{dt} \stackrel{!}{=} 0 \tag{36}$$

$$\tag{37}$$

Reformulation yields the welfare-maximizing tax rate

$$t^* = \frac{\lambda \frac{dE}{dt} - (v-1)E}{\frac{dq}{dt} + (v-1)\frac{dE}{dt}} \tag{38}$$

For $v \geq 1$ all terms are negative and the optimal tax rate is positive. Only if v is significantly smaller than unity, the optimal tax rate becomes negative. The optimal carbon tax increases in λ, the marginal damage of climate change, and v, the preference for tax revenues. For $v \to \infty$ the optimal rate is the revenue-maximizing rate $t^* = t_R^* = -\frac{E}{\frac{dE}{dt}}$. If $v > 1$ the optimal rate is larger than the marginal damages.

Result 1 *The optimal rate of carbon taxation is positive, unless the marginal costs of public finance are much below unity. The optimal tax rate increases in damages from climate change and in marginal costs of public finance. For $v > 1$ it is larger than the Pigouvian rate.*

Electricity Production

Electricity q is produced from two inputs, capital K and fossil fuels E. Fossil fuels are proportional to emissions. For example, burning a ton of coal releases to 2.7 tons of CO_2. Thus E represents a ton of carbon dioxide, or, equivalently, 0.37 tons of coal. A generic, well-behaved production function can be expressed as

$$q = q(E, K) \tag{39}$$

The price of q is p. Firms are price takers on output and input markets. Input prices are assumed to be constant and invariant to demand and are normalized to unity. Carbon is taxed such that the price of E is $(1+t)$. For consistency, the unit of capital has to be scaled accordingly. A representative maximize its profit

$$\pi = pq - E(1+t) - K \tag{40}$$

From the resulting first order conditions

$$p\frac{\partial q}{\partial E} \stackrel{!}{=} 1 + t \tag{41}$$

$$p\frac{\partial q}{\partial K} \stackrel{!}{=} 1 \tag{42}$$

the demand functions $E = E(K, t)$ and $K = K(E, t)$ can be derived. Substitution gives the demand functions

$$E = E(K, t) \tag{43}$$

$$K = K(t) \tag{44}$$

Further substitution could be done to derive $E = E(t)$, but it will be clear in a moment that this is not warranted.

6.2 Time Inconsistency: When and in which Direction?

Ex Post and Ex Ante Optimality

In the model there are two time periods. We are interested in the optimal tax rate in each periods. The only difference between periods is that in one period (the "ex ante" period) capital stock K is flexible, and in the other (the "ex post" period) K is fixed. The reason is that capital investments are irreversible. After investment decisions are made, they cannot be reversed. Thus "ex post" can be translated as "after investment decisions are made."

Accordingly, there are two investment demand functions for the two periods,

$$K_{ante} = K(t) \tag{45}$$

$$K_{post} = \bar{K} \tag{46}$$

which react differently on tax changes:

$$\frac{\partial K_{ante}}{\partial t} = \frac{\partial K}{\partial t} \tag{47}$$

$$\frac{\partial K_{post}}{\partial t} = 0 \tag{48}$$

This is why it was not possible to derive a simple carbon demand function $E = E(t)$.

We are interested in comparing the optimal ex post tax rate t^*_{post} to the optimal ex ante rate t^*_{ante}. Why? If t^* changes because of the investment decision, policy is time inconsistent. Indeed, this is precisely the definition of time inconsistency: The optimal policy is not the same over time. At this point we can formally define time inconsistency in the framework of the present model: *Policy is time inconsistent if* $t^*_{post} \neq t^*_{ante}$.

The direction of the change determines which effect time inconsistency has. If $t^*_{post} < t^*_{ante}$, time inconsistency causes what I have called a "downward pressure" or "downward bias" on carbon taxes. A downward bias means that the actual tax rate is lower than in the welfare optimum.

In the language of the time inconsistency literature, the ex ante and ex post rates are often called the “commitment” and the “discretion” (or “consistent”) solution. Under discretion, the social planer maximizes welfare taking expectations on taxes as exogenously given. He has to take expectations as given, because once the period one is over, decisions made in this period cannot be reversed. Ex post, once decisions are made, the discretionary solution is optimal. Before that, ex ante, the commitment rate was optimal. If both rates do not coincide, policy is time inconsistent.

Because the ex post rate is optimal after investments are made, always the ex post rate will be chosen. The ex ante rate is a hypothetical optimal tax rate, but will never emerge in practice. Because agents know the government will deviate from its ex ante optimal rate, the commitment solution is not feasible. Thus it is not actually two periods that we compare. Rather an hypothetical ex ante and an hypothetical ex post period are compared. The model does not describe two periods with two distinct tax rates, but a time-hierarchical decision-making process. Since agents know that after their investment decisions are made, the ex post rate will be chosen, they behave accordingly. However, if the government can commit to a tax rate, this is not the case: With commitment the ex ante rate will be chosen.

Any time inconsistency, no matter in what direction, is welfare-reducing. The commitment (ex ante) solution is the unique solution of the maximization of the welfare function. Any deviation from that solution must result in (strictly) less welfare than at the maximum. Time inconsistency can be viewed as the introduction of a further side constraint to the maximization problem. Any further constraints necessarily reduce the maximum value of welfare (if they are binding) or do not change it (if they are not binding). If the optimal tax rate changes, the new constraint is binding and welfare is strictly reduced.

Always the ex post rate emerges, but the ex ante rate is welfare-superior. Thus if $t^*_{post} < t^*_{ante}$, the tax rate that will emerge is smaller than the welfare-maximizing rate.

The Necessary Condition for Time Inconsistency

We are interested if, and in which direction, the optimal tax rate t^* (38) changes if capital K becomes sunk. For doing so, we substitute the two total derivatives from the expression of the optimal tax rate (38), using the demand functions (43) and (44):

$$\frac{dE}{dt} = \frac{\partial E}{\partial t} + \frac{\partial E}{\partial K}\frac{\partial K}{\partial t} \tag{49}$$

The total effect of taxes on emissions can be decomposed into the direct (partial) effect on emissions and the indirect effect via changes of capital. If the inputs are less than perfect substitutes, $\frac{\partial E}{\partial K}$ is always positive. If the total effect is smaller or larger than the partial effect depends on the sign of $\frac{\partial K}{\partial t}$. If $\frac{\partial K}{\partial t} > 0$, the total effect is smaller than the partial effect.

$$\frac{dq}{dt} = \frac{dq}{dE}\frac{dE}{dt} + \frac{dq}{dK}\frac{dK}{dt} \tag{50}$$

$$= \frac{\partial q}{\partial E}\left[\frac{\partial E}{\partial t} + \frac{\partial E}{\partial K}\frac{\partial K}{\partial t}\right] + \frac{\partial q}{\partial K}\frac{\partial K}{\partial t} \tag{51}$$

The effect of taxes on the amount of electricity produced can be decomposed into the effects of carbon taxes on both inputs multiplied with the effect of a change in inputs on electricity production.

The total effect $\frac{dE}{dt}$ is the ex ante effect of taxes on emissions and the partial effect $\frac{\partial E}{\partial t}$ is the ex post effect. Ex post, after investments are sunk, $\frac{\partial K}{\partial t} = 0$ by definition. Since the capital stock cannot be changed anymore, taxes simply cannot have any effect on capital. This means, ex post $\frac{dE}{dt} = \frac{\partial E}{\partial t}$; taxes can only have direct effects on emissions.

If for some reason $\frac{\partial K}{\partial t} = 0$ even ex ante, the ex post rate coincides with the ex ante rate, and there is no time inconsistency. If investments are invariant to taxes ex ante, there is no difference between ex ante and ex post - and there is no time inconsistency. Being true for all model parameters, including any value of v and λ and any function form of the production function q, this is a highly robust result. In the language of the ingredients for time inconsistency identified in section 3, time inconsistency requires that the persistent variable is a function of the decision variable of the regulating agent.

Why should investments be invariant to taxation even ex ante? In principle, taxes on one input (E) have two different effects on the other input (K). On the one hand, they increase the relative price of the taxed input, leading to substitution to realize the least-cost input combination for a given output quantity. This is the substitution effect. On the other hand, they increase the final price, leading to less demand, less production of output, and less demand for inputs. This is the quantity effect. The substitution effect of carbon taxes increases capital demand, the quantity effect reduces capital demand. If both effects cancel out, capital demand is invariant to carbon taxation.[13] In the Cobb-Douglas model of the next subsection I clarify

[13] Technically, this means the cross-price elasticity of capital is zero.

under which conditions the effects cancel out.

Result 2 *If investments are invariant to carbon taxes, there is no time inconsistency. This is true for the entire parameter space of* $\{v, \lambda\}$.

Without Public Finance

If we ignore public finance issues for a second, the can set $v = 1$. There are four reasons to do so: Economical empirical estimates of v, modeling philosophy, reference to the existing literature, and political empirical estimates.

Helm et al. (2004) argue that the marginal costs of public finance for energy taxes are most probably "slightly above unity". Given the uncertainty about this parameter, it is certainly not significantly different from unity in a statistical sense. Setting it to unity seems to be a reasonable approximation to reality Second, by abstracting from public finance, we concentrate on the climate change issues of the model. That means we can understand how climate policy in itself causes time inconsistency or not.

The third reason is that Helm at al. conclude that for $v = 1$ there is no time inconsistency. In the present model, however, this conclusion is reversed. Finally, today most emission permits are given away for free, e.g. in the EU ETS during phase I and II. This indicates that revenue generation has a very low priority in actual climate policy-making.

For $v = 1$ the optimal carbon tax simplifies to the Pigouvian rate

$$t^* = \lambda \frac{\frac{dE}{dt}}{\frac{dq}{dt}} \tag{52}$$

This can also be written as

$$t^* = \lambda \frac{dE}{dq} \tag{53}$$

If the ratio of E to q was fixed at unity, the optimal tax rate would be simply λ. In this case the two-good model becomes in fact an one-good model. The expression $\frac{dE}{dq}$ can be thought of as converting units of electricity to units of welfare from emissions.

Decomposing the total derivatives yields

$$t^*_{ante} = \lambda \frac{\frac{\partial E}{\partial t} + \frac{\partial E}{\partial K}\frac{\partial K}{\partial t}}{\frac{\partial q}{\partial E}\left[\frac{\partial E}{\partial t} + \frac{\partial E}{\partial K}\frac{\partial K}{\partial t}\right] + \frac{\partial q}{\partial K}\frac{\partial K}{\partial t}} \tag{54}$$

The optimal tax rate ex ante, when capital is still flexible, is given above (this is why it is denoted t^*_{ante}). The optimal tax rate ex post, when investments are sunk, is derived by simply setting $\frac{\partial K}{\partial t} = 0$

$$t^*_{post} = \lambda \frac{\frac{\partial E}{\partial t}}{\frac{\partial q}{\partial E}\frac{\partial E}{\partial t}} \tag{55}$$

If $\frac{\partial K}{\partial t} = 0$, both rates coincide and there is no time inconsistency.

We want to know which of the two rates is higher if $\frac{\partial K}{\partial t} \neq 0$. To do this analytically, we take the derivative of t^*_{ante} with respect to $\frac{\partial K}{\partial t}$. It can be show that

$$\frac{\partial t^*_{ante}}{\partial \frac{\partial K}{\partial t}} = -\lambda \frac{\frac{\partial E}{\partial t}\frac{\partial E}{\partial K}}{(\cdot)^2} > 0 \tag{56}$$

The first partial derivative in the numerator are negative, thus the expression is positive. This means that the ex ante optimal tax rate is higher than the ex post rate if capital investments are increased due to carbon taxation, and vice versa. Indeed, in the micro model below I show that under plausible assumptions $\frac{\partial K}{\partial t} > 0$.

Why is the optimal tax lower after investments are sunk, assuming that capital reacts positively on taxation? To answer this question we look closer how emissions and output reacts on a tax decrease, before and after investments are decided on. First take a look at emissions. If the tax is lowered before investments are sunk, emissions are increased both directly and indirectly via lower investments. After investments are sunk, emissions are increased only directly. Thus a tax decrease is *less costly* in welfare terms ex post than ex ante, since it induces less additional emissions.

Now look at electricity production. Before investments are sunk, a tax reduction had a positive effect on output due to increased uptake of fossil resources, but that was partly offset by an decrease in capital stock. After investments are sunk, this compensating effect is absent. Thus reducing the carbon tax is *more beneficial* in welfare terms ex post than ex ante, since it increases output stronger. Given that a reduction is less costly and more beneficial than before, the optimal tax rate is lower ex post.

Result 3 *For $v = 1$ there is a downward pressure on the optimal carbon tax rate due to time inconsistency if, and only if, capital investments react positively on increased carbon taxation.*

With Public Finance

Considering public finance issues ($v \neq 1$), things become more complicated. It is still true that reducing the carbon tax is more beneficial ex post than ex ante, since it increases output stronger (assuming $\frac{\partial K}{\partial t} > 0$). It is also true that it is less costly since it increases emissions less strongly. But now an additional effect comes into play: The effect on tax revenues.

Ex post, emissions are increased weaker than ex ante due to a tax reduction. Government likes this because of the climate externality. It does *not* like this because it increases tax revenues less. Tax reductions are *more costly* ex post than ex ante because they reduce revenues stronger.

One channel of time inconsistency (revenues) causes an upward bias on the carbon tax, and two channels cause a downward bias. Which dominates, depends on the relative weights of the channels, the parameters v and λ.

Take the extreme cases. For $v = 1$, we already know there is a downward bias on taxes. For $v \to \infty$, the optimal tax rate is $t_R^* = \frac{E}{\frac{dE}{dt}}$. Since $\frac{dE}{dt}$ is smaller ex post than ex ante, the optimal tax rate is larger ex post. Time inconsistency causes an upward bias on taxes. This reflects the "ratchet effect" often found in the investment and tax literature on time inconsistency.

While I can't provide an analytical proof, it is plausible to believe there is a threshold level v above which the time inconsistency bias becomes positive.

Since empirically v is "slightly above unity", I am confident that the overall effect is a downward bias.

Result 4 *For very high values of v there is an upward pressure on the optimal carbon tax rate due to time inconsistency if capital investments react positively on increased carbon taxation.*

6.3 Cobb-Douglas Production

The central result of the last subsection was that the reaction of investment due to carbon taxation crucially determines existence and direction of time inconsistency. Here $\frac{\partial K}{\partial t}$ is derived in a model with Cobb-Douglas production and constant elasticity of demand. The central result is that if, and only if, the price elasticity of demand is below unity in absolute value, capital investments are increased as a reaction on carbon taxes. Empirical evidence gathered from the literature indicate that the demand elasticity is below unity. The model is also illustrates the difference between ex ante and ex post reactions of emissions and output on taxation for an explicit production function.

Production Structure

Final energy output is produced with Cobb-Douglas technology using fossil resources E and capital K as inputs. Resources are scaled to coincide with emissions, such that E represents a ton of carbon dioxide, or, equivalently, 0.37 tons of coal.

$$q_t = E_t^\alpha K_{t-1}^\beta \tag{57}$$

K is predetermined in the sense that K has to be decided on one period in advance: Today's production depends on today's fossil fuel input and yesterday's investment decisions.[14] The power plant is built in one period, but used in the second period; and the amount of coal burned is decided on in that second period. This corresponds to a depreciation rate of capital of 100%. In other words, the period length is the life-time of a power plant. Investments are perfectly irreversible.

The current expected two-period profit equation for a representative firm is

$$\mathrm{E}(\pi_t + \pi_{t+1}) = pE_t^\alpha A_{t-1}^\beta + pE_{t+1}^\alpha K_t^\beta - K_t - E_t \cdot (1 + t_t) - K_{t+1} - E_{t+1} \cdot (1 + t_{t+1}^e) \tag{58}$$

where $\alpha, \beta < 1$. For simplicity, we abstract from discounting.

The price of output is p and firms are modeled as price takers. Given the high concentration of the electricity sector, this is a strong assumption. However, as I argue in section 8, it is a conservative assumption and not a crucial one. Taking into account market power would probably enforce my findings.

Input prices are assumed to be constant and invariant to demand and without loss of generality are normalized to unity. For consistency, the unit of capital has to be scaled accordingly. Taking input prices as given seems plausible since electricity markets are typically much smaller than the globalized market for fossil fuels and capital goods. The equation is given for the first period when the firm does not know t_{t+1}^e yet. The firm maximizes with respect to E_t, and K_t, the inputs bought in the current period. Since the optimal level of today's investment K_t depends on planned resource input E_{t+1}, it also maximizes with respect to future resources.

[14]The capital stock could also depend on both current and past decisions, or on a sequence of periods. While complicating the algebra significantly, this does not lead to qualitatively different results.

Maximization yields the three first order conditions

$$p(q_t)\alpha E_t^{\alpha-1}K_{t-1}^{\beta} = (1+t_t) \tag{59}$$
$$p(q_{t+1})\alpha E_{t+1}^{\alpha-1}K_t^{\beta} = (1+t_{t+1}^e) \tag{60}$$
$$p(q_{t+1})\beta E_{t+1}^{\alpha}K_t^{\beta-1} = 1 \tag{61}$$

Rather than being one system of linear equations, the three equations set up two independent systems. The first equation describes the behavior of variables that depend on t_t while the second and third equations describe variables that depend on t_{t+1}^e. Because 100% depreciation was assumed, both systems are independet.

Ex post behavior

Here we are interested in the behavior of variables *after* investments are sunk. This is expressed in the model as the reactions of variables if *current* taxes are changed.

Using (59) one can calculate the demand for energy as a function of current taxes, given a predetermined amount of capital K_{t-1}. The capital currently in use has been determined one period ahead and thus is perfectly inelastic to current changes of t_t. The demand for current energy input as a function of final energy prices is:

$$E_t(p) = \left(p(q_t)\cdot \alpha K_{t-1}^{\beta}(1+t_t)^{-1}\right)^{\frac{1}{1-\alpha}} \tag{62}$$

Demand for fossil fuels is higher for higher final energy prices and for higher given capital. Since K_{t-1} is fixed, there is no demand function for capital.

Plugging the equation into the production function and solving for q_t gives the output as a function of the tax rate, electricity price, and the given capital stock. This is the supply curve.

$$q_t = \left(p(q_t)\cdot \alpha K_{t-1}^{\frac{\beta}{\alpha}}(1+t_t)^{-1}\right)^{\frac{\alpha}{1-\alpha}} \tag{63}$$

Supply depends positively on the price and the capital stock, and negatively on taxes.

The supply curve is now used to derive the demand function for current energy input as a function of the electricity price p:

$$E_t(q) = q(p_t)^{\frac{1}{\alpha}}\cdot K_{t-1}^{-\frac{\beta}{\alpha}} \tag{64}$$

Because K is predetermined, no substitution can take place: All reaction on taxes work through a depression of output. For this reason t_t does not enter the demand function directly.

Ex Ante Behavior

Here we are interested how output and emissions react to tax changes *before* investments are sunk. This is the ex ante effect of carbon taxation. In the model this is described by the effect of *future* expected taxes. Combining (60) and (61) yields the well know optimal input relations for Cobb-Douglas technology:

$$\frac{K_t}{E_{t+1}} = (1 + t^e_{t+1})\frac{\beta}{\alpha} \tag{65}$$

Consequently,

$$E_{t+1}(p) = \left(p(q_{t+1}) \cdot (1 + t^e_{t+1})^{\beta-1}\alpha^{1-\beta}\beta^{\beta}\right)^{\frac{1}{1-\alpha-\beta}} \tag{66}$$

$$K_t(p) = \left(p(q_{t+1}) \cdot (1 + t^e_{t+1})^{-\alpha}\alpha^{\alpha}\beta^{1-\alpha}\right)^{\frac{1}{1-\alpha-\beta}} \tag{67}$$

Note that future energy demand deviates from current energy demand, since for the future capital is not fixed. The possibility to adjust the capital stock makes different energy input optimal. The planned supply function is

$$q_{t+1} = \left(p(q_{t+1})^{\alpha+\beta}\alpha^{\alpha}\beta^{\beta}(1 + t^e_{t+1})^{-\alpha}\right)^{\frac{1}{1-\alpha-\beta}} \tag{68}$$

Supply does not depend on the capital stock, because K_{t+1} is endogenous.

The demand functions for future energy and current capital can be derived:

$$E_{t+1}(q) = \left(q(p_{t+1}) \cdot (1 + t^e_{t+1})^{-\beta}\alpha^{\beta}\beta^{-\beta}\right)^{\frac{1}{\alpha+\beta}} \tag{69}$$

$$K_t(q) = \left(q(p_{t+1}) \cdot (1 + t^e_{t+1})^{\alpha}\alpha^{-\alpha}\beta^{\alpha}\right)^{\frac{1}{\alpha+\beta}} \tag{70}$$

Now t enters the demand functions directly and not only via q, because substitution between factors of production is possible. For given output q, carbon demand E depends negatively and capital demand K positively on the tax, but of course q is a function of the tax itself. q is not endogenized so far since no assumption about the demand function has been made. The next step is to compare the behavior K, q, and E on tax rate changes before and after investments are sunk.

Investment Demand K

Capital demand is affect by energy taxation through two channels that work in opposite direction. Substitution of capital for resources leads to higher demand. A reduction in electricity production leads to lower demand. It will be shown that it is the price elasticity of electricity demand η determines which effect dominates.

Taking the derivative of the demand function (70) with respect to taxes t^e_{t+1} shows the two channels analytically:

$$\frac{dK_t(q)}{dt^e_{t+1}} = \frac{1}{\alpha+\beta} K(\frac{\partial q}{\partial t}\frac{1}{q} + q\alpha(1+t^e_{t+1})^{-1}) \tag{71}$$

The first term in parenthesis is negative and represents the quantity effect. The second term is positive and represents the price effect.

From this, we derive the elasticity of investment demand with respect to taxes $\epsilon_{K_t,t_t} = \frac{\partial K}{\partial t}\frac{t}{K}$. Ex post, We know that $\epsilon_{K_t,t_t} = 0$ by definition, since K is predetermined.

Ex ante, for emissions and for output the direction of the reaction is clear a priori (a reduction). We were merely interested in the magnitude of the reaction (larger or smaller than ex post). For investment demand, the direction is not clear.

The elasticity of investment demand with respect to future expected taxes is derived. This is the cross-price elasticity between inputs. It is:

$$\epsilon_{K_t,t^e_{t+1}} = \frac{\partial K_t}{\partial t^e_{t+1}}\frac{t^e_{t+1}}{K_t} \tag{72}$$

$$= \frac{\alpha(\eta+1)}{(\alpha+\beta)-\eta(1-\alpha-\beta)}\frac{t_{t+1}}{1+t^e_{t+1}} \tag{73}$$

where $\eta = \frac{\partial q}{\partial q}\frac{p}{q}$ is the price elasticity of demand (the % change of electricity demand for a 1% increase in electricity price). Households are not modeled explicitly, thus η is directly determined by the demand function. η is negative for normal goods. For $|\eta| < 1$, demand is called “inelastic”, and for $|\eta| > 1$ “elastic”. As $|\eta| \to 0$, demand is called “perfectly inelastic”, and for $|\eta| \to \infty$ “perfectly elastic”. Perfectly inelastic means output q is fixed, perfectly elastic means price p is fixed.

If $|\eta| < 1$, the elasticity $\epsilon_{K_t,t^e_{t+1}}$ is positive and capital input rises if future taxes are expected to increase. If $|\eta| = 1$ both effects cancel out and capital demand is invariant to future taxation. If $|\eta| > 1$, a future tax increase depresses output s0 much that this dominates the substitution effect and in sum capital demand falls. If the tax level is zero the effect of a marginal tax increase on capital is zero due to the Envelope theorem.

To gain some intuition for this result, consider three special cases. For zero output demand elasticity, investment demand elasticity is highly positive. For fixed output, higher energy prices lead necessarily to a substitution of energy by capital, leading to higher capital demand. In this extreme case, there is only a substitution effect. For infinite output demand elasticity, there is still substitution of capital for fossil fuels, but output slumps so much that overall capital demand decreases. If demand elasticity equals unity, both effects just cancel out.

$$\begin{aligned}
\epsilon_{K_t,t^e_{t+1}} &= \frac{\alpha}{\alpha+\beta}\frac{t_{t+1}}{1+t^e_{t+1}} > 0 && \text{for } \eta = 0 \text{ (fixed } q\text{)} \\
\epsilon_{K_t,t^e_{t+1}} &= 0 && \text{for } \eta = -1 \\
\epsilon_{K_t,t^e_{t+1}} &\to -\frac{\alpha}{1-\alpha-\beta}\frac{t_{t+1}}{1+t^e_{t+1}} < 0 && \text{for } \eta \to -\infty \text{ (fixed } p\text{)}
\end{aligned}$$

Result 5 *Capital input rises due to expected higher future taxes if $|\eta| < 1$. If $|\eta|$ is unity, investment is invariant to future taxation. If $|\eta| > 1$, investments decrease if future taxes are increased.*

Given the result 3, it follows that there is a downward bias on carbon taxes due to time inconsistency if $|\eta| < 1$ (ignoring public finance issues).

Electricity Output q

For a general production function, (50) clarifies the difference between ex ante and ex post reactions of output to a carbon tax increase. However, even if capital increases due to taxation (as shown in the last subsubsection), it is not clear from (50) if q reacts stronger or weaker ex post than ex ante. In the following paragraphs is is shown that under a Cobb-Douglas setting q reacts stronger ex post.

First, consider the ex post behavior. Taking derivatives of the demand for energy with respect to taxes using the chain rule and rearranging items yields the elasticity of output with respect to taxation:

$$\epsilon_{q_t,t_t} = \frac{\partial q_t}{\partial t_t}\frac{t_t}{q_t} = \frac{\alpha\eta}{\alpha-\eta(1-\alpha)}\frac{t_t}{1+t_t} < 0 \tag{74}$$

Then, consider the ex ante elasticity

$$\epsilon_{q_{t+1},t^e_{t+1}} = \frac{\partial q_{t+1}}{\partial t^e_{t+1}}\frac{t^e_{t+1}}{q_{t+1}} = \frac{\alpha\eta}{(\alpha+\beta)-\eta(1-\alpha-\beta)}\frac{t^e_{t+1}}{1+t^e_{t+1}} \tag{75}$$

Now we can compare quantity reactions. Compare (74) with (75) to see if ex ante or ex post output reacts stronger to tax changes. Under the assumption of rational expectations $t^e_{t+1} = t_{t+1}$, thus we actually compare the effect of current tax changes with the effect of future tax changes. The ration of ex-post to ex-ante elasticities is:

$$\frac{\epsilon_{q_t,t_t}}{\epsilon_{q_{t+1},t_{t+1}}} = \left(1 + \frac{\beta(1+\eta)}{\alpha - \eta(1-\alpha)}\right) \frac{\frac{t_t}{1+t_t}}{\frac{t^e_{t+1}}{1+t^e_{t+1}}} \tag{76}$$

For any given tax rate the last fraction cancels out.

The second term in parenthesis becomes positive if η is smaller than unity in absolute value. If this is the case, quantity is reduced stronger if current taxes are increased compared to an increase of future taxes. Output reacts stronger after investments are sunk. The economic intuition behind this important result is that on current taxes firm can only adjust by reducing output - on future taxes, they have the second option of substitution energy for capital.

$$\epsilon^{post}_{q,t} > \epsilon^{ante}_{q,t} \qquad \text{for } |\eta| < 1 \tag{77}$$

If output is highly price elastic (above unity), the opposite is true. The reason is that then future tax increases lead to a reduction of investment demand, diminishing output further. Current tax increases do not have this effect since the current capital stock is fixed. The special cases:

$$\frac{\epsilon^{post}_{q,t}}{\epsilon^{ante}_{q,t}} = \frac{\alpha+\beta}{\alpha} > 1 \qquad \text{for } \eta \to 0 \text{ (fixed } q)$$

$$\frac{\epsilon^{post}_{q,t}}{\epsilon^{ante}_{q,t}} = 1 \qquad \text{for } \eta = 1$$

$$1 > \frac{\epsilon^{post}_{q,t}}{\epsilon^{ante}_{q,t}} = \frac{1-\alpha-\beta}{1-\alpha} > 0 \qquad \text{for } \eta \to -\infty \text{ (fixed } p)$$

Result 6 *For any given tax rate, quantities react stronger to tax changes after investments are sunk if and only if $|\eta| < 1$. If $|\eta| = 1$, quantity reactions are the same ex post and ex ante. If $|\eta| > 1$, quantities react weaker once investments are sunk.*

Emissions E

Now we turn on emissions. From (49) we know that the ex post elasticity has to be lower than the ex ante elasticity. This is confirmed in the following for an explicit Cobb-Douglas production function.

The ex post reaction of taxation on emissions can be derived as

$$\epsilon_{E_t,t_t} = \frac{\partial E_t}{\partial t_t}\frac{t_t}{E_t} = \frac{1}{\alpha}\epsilon_{q_t,t_t} \tag{78}$$

$$= \frac{\eta}{\alpha - \eta(1-\alpha)}\frac{t_t}{1+t_t} \tag{79}$$

Emissions react proportional to output, since for fixed K no substitution takes place. Energy consumption decreases if it is taxed.

The ex ante price elasticity of energy demand with respect to carbon taxes is the own-price elasticity of energy (recall energy prices were normalized to unity). This is:

$$\epsilon_{E_{t+1},t^e_{t+1}} = \frac{\partial E_t}{\partial t^e_{t+1}} \frac{t^e_{t+1}}{E_t} = \frac{1}{\alpha+\beta}\left(\beta + \epsilon_{q_{t+1},t_{t+1}}\right) \tag{80}$$

$$= \frac{1}{\alpha+\beta} \frac{\eta\beta(1-\alpha-\beta) - \eta\alpha - \beta(\alpha+\beta)}{(\alpha+\beta) - \eta(1-\alpha-\beta)} \frac{t^e_{t+1}}{1+t^e_{t+1}} \tag{81}$$

The ration of ex post to ex ante elasticity of emissions with respect to taxes is:

$$\frac{\epsilon_{E_t,t_t}}{\epsilon_{E_{t+1},t_{t+1}}} = \left(\frac{\alpha+\beta}{\alpha} \frac{\eta}{\alpha - \eta(1-\alpha)} \frac{(\alpha+\beta) - \eta(1-\alpha-\beta)}{\alpha\eta - \beta[\alpha+\beta-\eta(1-\alpha-\beta)]}\right) \frac{\frac{t_t}{1+t_t}}{\frac{t^e_{t+1}}{1+t^e_{t+1}}} \tag{82}$$

The solution to this expression is not obvious at the first glance. I was not able to derive an algebraically more elegant expression. However, simulations show that this ratio is weakly smaller than unity for any values of α and β. It equals unity for $|\eta| = 1$ and is strictly smaller for any other value of η. For sensible parameters of α and β is is always positive.

$$\epsilon^{post}_{E,t} < \epsilon^{ante}_{E,t} \qquad \text{for } |\eta| \neq 1 \tag{83}$$

The special cases:

$$\frac{\epsilon^{post}_{E,t}}{\epsilon^{ante}_{E,t}} \rightarrow 0 \qquad \text{for } \eta \rightarrow 0 \text{ (fixed } q)$$

$$\frac{\epsilon^{post}_{E,t}}{\epsilon^{ante}_{E,t}} = 1 \qquad \text{for } \eta = 1$$

$$\frac{\epsilon^{post}_{E,t}}{\epsilon^{ante}_{E,t}} \rightarrow 0 \qquad \text{for } \eta \rightarrow \infty \text{ (fixed } p)$$

Why is this the case? First take the special case of $\eta = 1$. We know in this case current capital is invariant to future taxation since output and substitution effect just cancel out. Thus capital is "fixed". In other words, there is no difference between current and future capital in terms of its reaction on taxation: There is none. In the former case because current capital is sunk and cannot be changed, in the latter case due to the cancellation of output and substitution effect. Under this condition the other factor of production, energy uptake, has to react equally on taxation, before investment is sunk and after.

If demand is less elastic, the substitution effect dominates the output effect for investment demand and capital is increased if taxes are increased. As a consequence, emissions are reduced twofold: By lowering the output and by producing more efficiently. Thus the reduction in emissions is stronger ex ante, when there is still the possibility to change K. The ex post elasticity is lower than the ex ante elasticity.

If demand is even more elastic than unity, the ex post elasticity is also lower than the ex ante elasticity. Under this condition, investments are reduced if future taxes are increased. Less capital makes even less energy input optimal, a consequence of the complementarity of both production factors.

Result 7 *For a given tax rate, emissions always react weaker to tax increases after investments are sunk. The only exception is the special case $\eta = 1$, where there is no difference between the ex-ante and ex-post elasticity.*

Empirical Elasticity of Demand for Final Energy

The price elasticity of demand $\eta = \frac{\partial q}{\partial p}\frac{q}{p}$ describes by how much percentage demand changes if the price is increased by one percent. It is determined by the demand function, itself being the result of utility-maximizing households (this is not modeled in the present paper). In general the price elasticity is not constant, but a function of the price itself. A constant elasticity of demand function $q = p^{\eta}$ is a special case.

What determines the elasticity of demand? Demand reactions work through an income and a substitution effect at the household level. If there is a close substitute available, the demand elasticity for a good is normally very high. Typically demand reacts the more elastic the longer the time frame under investigation is. Electricity consumed by households, for example, can in the short run almost only be reduced by reducing consumption: Switching off the lights, turning off the air conditioning, or washing by hand. In the medium run, more efficient equipment can be bought and energy-saving light bulbs replace standard bulbs. In the very long run, even architecture and city planning can be adjusted to changes in energy prices. Thus long-run elasticities are always larger in absolute value than short-run elasticities.

Espey and Espey (2004) have recently conducted a rigorous meta-analysis of empirical studies on the price elasticity of demand for final energy. Drawing on more than 120 estimated elasticities, they report short-run elasticity to be in the range of -2.01 to -0.00 with a mean of -0.35 and a median of -0.28. As expected, in the long run demand is much more elastic, with a range of -2.25 to -0.04, a mean of -0.85 and a median of -0.81. Given these estimates it seems plausible to believe η to be larger than zero but smaller than unity is absolute value. Since we are mainly interested in the long run, I take the range of -0.8 to -0.9 as a plausible parameter range. The reason for electricity demand being inelastic is that there are no close substitutes for electricity available.

Result 8 *The elasticity of demand η is a central parameter to the model. If $|\eta| < 1$ or not determines qualitatively the results. Empirically, we can be pretty confident that the demand for final energy is inelastic* ($|\eta| < 1$).

The Downward Bias of Time Inconsistency

What have we learned from this? A fundamental result is the central role of demand elasticity: If the demand elasticity is below unity, capital input increases due to a rise of future taxes. As a consequence, output is reduced more heavily ex post than ex ante, and the opposite is true for emissions: The ex post elasticity of output is *larger* than the ex ante elasticity. The ex post elasticity of emissions is *smaller* than the ex ante elasticity. Empirically, the demand elasticity of energy is below unity.

To sum up, under plausible assumptions about the elasticity of demand, output reacts quicker to tax increases after investments are sunk, but emissions react slower. The reason is that capital increases ex ante if taxes are increased, but it cannot increased ex post when it is sunk. Tax decreases are more beneficial and less costly ex post than ex ante. As a consequence, the ex post optimal tax rate is lower than the ex ante optimal tax rate (assuming v is not too large).

$$t^*_{post} < t^*_{ante} \tag{84}$$

In other words, due to time inconsistency, climate policy is less tight than it should be to maximize welfare.

Result 9 *Time inconsistency causes climate policy to be too soft.*

Effects on Output, Emissions, and Investments

We know, assuming $|\eta| < 1$, that the consistent tax rate is lower than the optimal (commitment) rate. This means time inconsistency reduces welfare. We are also interested how time inconsistency affects final energy output, emissions, and investments. To derive this, we have to specify the demand function for final energy. I assume that demand exhibits constant price elasticity and can be written

$$q = p^\eta \tag{85}$$

where η is as before the price elasticity of demand.

The welfare-maximizing tax rate is t^*_{ante}. Firms anticipate rationally that the tax rate that will emerge in fact is $t^*_{post} < t^*_{ante}$. Now we can compare the actual outcome with the welfare-maximizing outcome.

Given that formulation the future supply function (68) can be written as

$$q_{t+1} = (\cdot)(1 + t^e_{t+1})^{\frac{-\alpha\eta}{\eta(1-\alpha-\beta)-(\alpha+\beta)}} \tag{86}$$

where $(\cdot)$ as a positive expression of αs and βs. The exponent is strictly negative. Output depends always negatively on tax rates. Since the actual (ex post) tax rate will small than the welfare-maximizing (ex ante) tax rate, actual output will be higher than optimal output.

Future emissions (69) can be written as

$$E_{t+1} = (\cdot)(1 + t^e_{t+1})^{\frac{-\alpha\eta}{\eta(1-\alpha-\beta)-(\alpha+\beta)} - \beta} \tag{87}$$

The exponent is strictly negative and larger in absolute value than the exponent in the supply curve. This means emissions depend always negatively on taxes. Thus actual emissions will be higher than optimal emissions. The increase relative to optimal emissions is larger than for output.

Current investment demand (70) can be written as

$$K_t = (\cdot)(1 + t^e_{t+1})^{\frac{\alpha(\alpha+\beta)(1-\eta)}{\eta(1-\alpha-\beta)-(\alpha+\beta)}} \tag{88}$$

Capital demand depends positive on the tax rate if and only if the price elasticity of demand is less than unity in absolute value. We have seen empirical this is the case. Thus actual investments are smaller than optimal investments.

Result 10 *If demand is little elastic, time inconsistency drives down the tax rate below its optimal value. This causes final energy output as well as emissions to be inefficiently high and investments to be inefficiently low.*

7 Commitment Devices

The literature review of section 5 and the model outlined in section 6 have showed that time inconsistency is a serious problem in carbon-pricing climate policies such as a carbon tax or a cap and trade system. Being able to commit to a pre-announced carbon price would often be better for welfare and for the climate. For sovereign states, commitment is not easy and designing binding contracts is a difficult task. At the end, states have the monopoly on violence and can reverse any existing law if they really want to. In the words of Daron Acemoglu, "parties holding political power cannot make commitments to bind their future actions because there is no outside agency with the coercive capacity to enforce such arrangements" (Acemoglu 2003). To put it differently, perfect credibility is not possible. However, a number of mechanisms can be used to obtain some credibility with respect to future climate policy. These mechanisms are called commitment devices.

I classify commitment devices into three categories. On the one hand, efficient carbon pricing instruments can be modified. Two sets of modifications are possible: Changing the policy itself, or changing the institutional environment of how policy is designed. On the other hand, market-based instruments can be partially or fully replaced by other instruments such as research subsidies, feed-in tariffs, or command and control policies.

Political scientists use the Anglo-Saxonian concepts of *polity*, *policy*, and *politics* to capture different dimension of what most other languages describe as "Politik" (German), "politique" (French) or "política" (Spanish). Polity describes the institutional arrangement, the role and power different agents have, and the relative power of bodies of the state. Policy is the output: Laws, regulation, decisions, or plans. Politics is the process in which polity produces policy. It covers the struggle between different interests, negotiations between actors, and the finding of compromises.

I conclude that change the institutional framework for carbon policy is difficult. Specifically, establishing an autonomous "carbon bank" is not an effective response to time inconsistency. Moreover, it raising severe issues of democratic legitimacy, even more than independent central banks. There are a number of policies that make carbon pricing instruments more credible, but their scope is limited. The most important policy is to establish a legally binding, clearly defined reduction target and build independent monitoring institutions. Policies other than carbon pricing can be much more credible, but are in general less efficient. Finally, I propose two alternative interpretations why some policies are more credible than others.

7.1 Carbon Pricing: Polity

In academia, but even more in policy circles some debate is going on about the possible establishment of "carbon banks" or "energy agencies", autonomous institutions that conduct climate policy similar to central banks conducting monetary policy (Edenhofer et al. 2009b, Helm et al. 2004).[15] "Conducting climate policy" here means to set the parameters of a carbon pricing policy, most importantly the carbon tax rate in a price regime or the cap in a quantity regime.

Traditionally, the literature on time inconsistency in monetary policy focuses much on institutional design, or polity, to find commitment devices. As described in section 4.2, economist usually see independence as a necessary but not sufficient condition to establish welfare-optimal inflation rates. It has been show that independence in conjuncture with a long-living institution, with a biased management, or by assigning explicitly a single target are possible options.

This section discusses how these findings translate to climate policy. I believe it is much harder to design an independent institution for climate than for carbon policy, mainly for the long time horizon necessary and the uncertainty involved in climate policy.

The feasibility to create an autonomous carbon bank and its implication for democracy are also discussed.

Creating a Carbon Bank

Is it feasible to set up a autonomous institution regulating climate policy? Is the establishment of a carbon bank politically feasible? Are democratic (and other) institutions willing and able to voluntarily hand over power to other, newly established institutions?

Climate policy affects fundamentally welfare and economic power as well as income distribution through its effect of final energy prices. It also affects strategic interests of states by touching up on crucial issues of dependence from suppliers of fossil fuels, biomass, electricity, or other resources. Thus giving up regulatory authority on climate policy means a substantial loss of real power for government and parliament. Given the existing literature in political science it probably makes sense to distinguish between establishing a new national institution (handing over power from one national state body to another) and multilateral integration (handing over

[15] See also http://www.euractiv.com/en/future-eu/miliband-sees-21st-century-eu-low-carbon-power/article-168457 and http://news.smh.com.au/national/industries-warming-to-carbon-bank-idea-20081117-690y.html

power from the state to a supranational institution).

According the the classical theory of bureaucracy as developed by, inter alia, sociologist Max Weber (Weber 1922) and economist William A. Niskanen (Niskanen 2007) political institutions aim to accumulate power and increase their budget as well as regulatory reach. Following this line of argument, executive and legislative bodies would not voluntarily hand over power to another institution.

But the history of monetary policy shows exactly this: The voluntary transition of substantial power from parliaments and governments to new independent national institutions. Monetary policy has huge effects on the macro economy in the short run, and any democratic government is entrapped to use this efficient tool to boost economic growth when facing elections. However, during the 1980s and 1990s a large number of countries have handed over that power to independent central banks. This shows impressively that democratic governments are able and willing to give up and limit their power if there is the perceived need to do so.

But it is probably not academic arguments and theoretical reasoning that lead political institutions to give up power. Almost in every single case countries have made very bad experiences with governmental-run monetary policy before independent central banks were established. Rather than by deductive insights, the process was driven by trial and error, with very high social costs. A prominent case is Germany. Germany's *Bundesbank* is *the* case of an independent central bank with a successful history of inflation abatement. The Bundesbank was established in 1949 as the "Bank deutscher Länder". Many historians and politicians back then as well as today regard the hyperinflation in 1922/23 and the consequent economic bust as a leading factor in the destabilization of the Weimar Republic and the German democracy. Having experienced Hitler's World War II and the Holocaust, taken together with a plausible "Inflation to Hitler" hypothesis made the establishment of an independent central bank possible.

Also the wave of independent central banks established in emerging economies during the 1970s, 1980s, and 1990s followed severe monetary and economic crisis. Chile's *Banco Central*, another prominent case of successful CBI, was established after Augusto Pinochet's coupe d'état in 1973 and followed a time three-digit inflation, violent turmoil, and fierce repression after the coupe.

In several Latin American countries fairly independent central banks were established after the decade-long recession of the 1980s. The most prominent case is Argentina. For most of the period between 1975 and 1990, Argentina experienced hyperinflation (averaging 325% a year), poor or negative GDP growth, a severe lack of confidence in the national government and the Central Bank, and low levels of capital investment. After eight currency crises since the early 1970s, inflation peaked in 1989, reaching 5,000% that year. GDP was 10% lower than in 1980 and per capita GDP had fallen by over 20%. Fixed investment fell by over half and, by 1989, could not cover yearly depreciation - particularly in the industrial sector. Social indicators deteriorated seriously: Real wages collapsed to about half of their 1974 peak and income poverty rates increased from 27% in 1980 to 47% in 1989 (World Bank, ed 1993). In 1991 a so called "Currency Board" was established, taking government and parliament virtually any formal and informal way to influence monetary policy. Besides a monetary union, a currency board is the most radical way to give up power in monetary policy. It might well be argued that a currency board is just the opposite of an independent central bank. But the point is that it took several long and very deep economic crises for the Argentinian government to give up the monetary authority.

An alternative to establishing an independent national carbon bank is to hand over regulatory competences to a multilateral institution. Not always, but often, such supranational institutions have a considerable degree of independence from governments. Since they aggregate the interests of several countries, by definition they are at least somewhat independent from every single government. Thus multilateral integration is a means to establish independence.

The literature in international relations in general and integration specifically is vast and even a short review is far beyond the scope of this text. The same is true for the historical and political practical experience with integration. According to the founders of classical realism such as Carr (1939) and Morgenthau (1948) states act like rational choice power maximizers. In their theory integration has little room, if not to unify forces to combat a dominant hegemon. More recent theories such functionalism (with its leading proponent David Mitrany), neo-functionalism (Ernst Haas), neo-realism (Kenneth Waltz), constructivism (Alexander Wendt), or interdependence theory (Robert Keohane) have proposed arguments to explain multilateral integration.

Of course European integration over the last 60 years is the leading example of democratic institutions handing power over to new supranational institutions. Many of the policies now decided up on mainly at the European level are central to economic policy, such as the common market. Other well know examples of successful multilateral integration include the NATO in security policy and the WTO in trade policy. So it might well be asked, if governments restrict their ability to determine trade, security, and industrial policy, why should they not be able to give up their right to set the carbon price?

To sum up, both theory and historical evidence suggest that indeed institutions are highly reluctant in giving away power. But theory and evidence also show that under certain conditions they anyway do it. Often in history this has happened as the consequence of a costly trial and error learning process. This is not an option for climate policy. As Steffen Brunner has put it, while playing a repeated game on inflation has resulted in much political damage and considerable social costs, playing a repeated game with the only planet we have would be pretty risky.

While this is far from being a final judgment, I believe the UNFCCC process, the Kyoto protocol with its binding emission targets, and the highly important role the EU play in European climate policy all show that there is a real chance for multilateral decision making in climate policy.

Thus I believe something similar to a "carbon bank", being an independent national or a multilateral institution, could realistically be established within the next decade or so.

Long-living Institutions

A solution proposed in the context of monetary policy is to set up autonomous institutions that are much more long-lived than democratic governments typically are. I believe this argument does not hold for climate policy. The time horizon for climate policy is simply much too long.

Monetary policy has an effect if and only if nominal prices are sticky. This is the case if contracts are fixed in nominal terms without being indexed, for example as many labor contracts are. Labor contracts are in effect usually for a time period of less than two years. Given the fact that a substantial part of all contracts has a considerable shorter duration (many virtually zero), the average periods is probably around one year. In other words, a time period in a monetary policy model represents one year.

The mechanism modeled in section 6 is based on sunk investment in fixed capital. Large-scale investments in power plants and complementary technologies such as grids, storage facilities, or CCS are done taking into account *much* longer time frames. Coal-fired power plants often run for 40 years or more. Nuclear power plants are designed to run for about 20 years, but in fact some of them are in service for more than 40 years. The *Walchenseekraftwerk* in Bavaria is a water power plant that runs for more than 60 years. According to Janosch Abegg, an official from the Norwegian utility *Statkraft*, power suppliers take a time horizon of about 45 years when deciding upon investments.[16] Thus a time period in a climate policy model

[16]This statement was made at the conference "Klimaverträgliche Energieversorgung" organized by the Humboldt Forum Wirtschaft, 2009/06/10 in Berlin.

represents 45 years.

While central bankers can gain considerable reputation within the life-time of generation or even within the tenure of a central bank officer by bringing down or stabilizing inflation, this is clearly not the case for the transition to a low-carbon society. He will be dead by the time his policy develops major impact. It is hard to believe that a carbon banker could take an infinite period game perspective if even the second period of the game will take place after his life-time.

An Environmentalist Carbon Banker

Drawing on Rogoff's (1985) proposal to install a "conservative central banker", some authors have proposed to elect an "environmentalist carbon banker". Formally, this is represented in the model as a person that has a larger weight λ in its preference function than society. Indeed, looking at equation (38) it is clear that by adjusting λ any tax rate could be accomplished. For example, λ could set in a way that the rate ex post chosen by the carbon bank coincides with the ex ante welfare-maximizing rate. While time consistency would still exist, its consequences were be counterbalanced. Obtaining the unconstrained optimal social welfare solution is feasible.

Maybe the "environmentalist central banker" could not be taken too literal. Climate policy is highly complex, involving several layers of governmental power and a very broad range of legislation. Rogoff's argument can be interpreted in the way that the aggregate outcome of climate policy making is biased towards climate protection: On average, the actors involved in climate policy should be more environmentalist than society.

This could be accomplished, for example, by assuring a powerful veto player with significant vested economic or reputational interests in climate protection. For European climate policy, an institution of the European Union could play that role. Maybe the European Commission or the European Parliament could be such a player. Indeed, the Parliament has often been in favor of more and stronger climate protection, proposing more stringent reduction targets, less exceptions for industry, and quicker implementation. Often the European Council was on the other side of the spectrum, proposing soft targets, many exceptions, and slow implementation. The Commission has often hold an intermediate or a soft pro-climate position. Buchner et al. (2006) have termed the Commission an "enforcer of scarcity" for its hard position against national governments and the Council.

An example of these roles can be found in the negotiations about the third trading phase of the EU Emission Trading Scheme that took place during 2008. The proposal by the Commission launched in January 2008 was considerably stringent. It was further tightened in several aspects by the European Parliament, including earmarking revenues to climate policy, the possibility to import allowances, and free allocation for industry. In December the Council decided on the legislation during its Luxembourg meeting. It allowed free allocation of certificates for a large part of industry, and even the power sector in some central-eastern European countries, making the package much softer than the original proposal.

Thus introducing a "pro-climate bias" into European climate policy could be implemented by giving more power to the European Parliament or the European Commission.

However, in the context of long-run policy making and long-run investment decisions, it has to be assured that the pro-climate protection bias of policy is guaranteed over the next decades - and this what is needed to change the expectations of investors. It is hard to see how this should be done in a democratic system with changing majorities. A new parliament might well be pro-industry rather than be pro-climate.

In addition, the institutional structure of the European Union itself is far from being clear even in the short run. With the Lisbon treaty still hanging in the balance, no one can predict the role of the Parliament or the Commission even three years ahead. How should such a role be assured for decades in the future?

As a consequence, I do not believe it is feasible to solve the problem of time inconsistency by introducing consciously a pro-climate bias to policy making. The time horizon under consideration is too long.

A Single Target

The third mechanism to make independence a solution to dynamic inconsistency is to assign a single target to the regulation institution, instead of using the social welfare function as the objective function. In the case of monetary policy, the ECB has been set only a single primary target, namely to keep inflation below two percent. For a carbon bank, assigning a single target means to neglect the other components of the social welfare function (24) and set the bank a loss function that has to be minimized. In such a loss function only emissions play a role

$$L = (\bar{E} - E)^2 \tag{89}$$

where $\bar{E}$ is an emission target. Alternatively, other targets could be set, such as damages from climate change, degrees of global warming, or the atmospheric CO_2 concentration.

For monetary policy this is an attractive solution, since the optimal inflation rate is rather undisputed (say, somewhere between 1% and 3%) and, even more important, the optimal inflation rate is stable in the medium to long run. There is no reason to believe the optimal inflation rate over an entire business cycle today is different from the optimal rate during the 1970s or the 2030s. In addition, there is no real or long-run trade-off between unemployment and inflation. The trade-off is very short-term (about one year), thus assigning a fixed inflation target to the central bank might harm welfare over this time period, but not afterwards.

Because there is no long-term trade-off, identifying the exact true social preferences for unemployment, consumption losses, and inflation is not too important. If the central bank uses "wrong" preferences, all it can do is cause damage in the very short run. In climate policy, however, there *is* a long-run deep trade-off between consumption and climate protection. This means it is very important to find out the true preferences society has.

Are there objective and accepted ways to determine the emission amount of emission reductions? In theory, yes, in practical terms, no. The optimal degree of climate protection is far from being resolved. As mentioned in section 2, Nordhaus and Stern, two climate economists, have estimated the welfare-maximizing global warming target to be 3.6° C and 1.5° C, respectively.

This looks like a ratio of $3.6/1.5 = 2.4$ which might sound considerably close. But the difference for emissions and thus the implications for policy are widely different! With a climate sensitivity of 2.5, the Stern target translates to an atmospheric CO_2 concentration of 430 ppm, only 50 ppm more than today. The Nordhaus target implies a concentration of 770 ppm, 390 ppm more than today. In other words, the Nordhaus target implies almost *eight times* more emissions than Stern. Given this large discrepancy, it is pretty obvious that there is no consensus about the optimal degree of emission reduction.[17]

Furthermore, new knowledge about the climate system, climate sensibility, and socioeconomic factors such as the costs of GHG abatement are emerging continuously and at a high speed. As a consequence, the optimal degree of climate policy has to be adjusted over and over again. Under these condition, it is much harder to assign a clear, simple, and transparent target to a carbon bank than to a central bank. What is the optimal level of emissions $\bar{E}$? If new information leads to a downward revision of $\bar{E}$, how can investors be sure that this was indeed due to

[17] These numbers were derived in a very simple first approximation estimate as follows: $\Delta T = \alpha ln((K_{2009} + X)/K_0)$ where ΔT is the temperature increase, K_0 is the pre-industrial CO_2 concentration of 280 ppm, K_{2009} is the current concentration of 380 ppm X is the remaining increase in concentration, and $\alpha = 3.6$ is a parameter. This values implies a climate sensitivity of $\alpha ln2 = 2.5$.

new information and not due to time inconsistency? Until these question can be answered, it is hard to see how a single target for climate policy could work.

To sum up: Because climate policy involves a long-run trade-off, a single target is only legitimate if it is widely agreed on. One the one hand, the optimal target is far from clear, on the other hand it will change dramatically with new information emerging. In total, this makes a single-target solution clearly infeasible.

Democratic Legitimacy of a Carbon Bank

The idea of delegating policy making to an autonomous technocratic institution rises serious questions of democratic control, legitimacy of power, and accountability. At the most fundamental level, independence is at odd with the idea of democracy, since under an independent carbon bank the sovereign looses its influence on policy decisions.

Social scientists others than economists, such as historians, political scientists, and sociologists often criticize this lack of democracy (Elgie 1998). Berman and Mcnamara (1999) summarize their article in *Foreign Affairs* on Central Bank Independence with the statement: “As the world gets more democratic, central banks get more undemocratic. These powerful institutions should not be exempt from popular control.” They attack especially the European Central Bank for “its almost complete freedom from democratic oversight and control.”

In the formal model above it is assumed that a “social welfare function” exists, is stable, and is well known. In fact, democratic political systems with their political parties, elections, parliaments, and governments can been seen as complex mechanisms to identify and aggregate the interests and preferences of their citizen and to translate them into policy decisions. How should a central banker know how people weight unemployment or consumption losses against inflation? How could a carbon banker find out what weight climate protection has for society? Democratic systems are mechanisms to aggregate information, and to me it is not clear how bankers could substitute them.

Here an important difference between monetary policy and climate policy resurfaces. Since according to the classical model of monetary policy, there is no trade-off between inflation and output after the short run, central bankers cannot do to much harm by choosing the wrong social preferences. If there is no important decision to be made, lacking participation can be accepted.

But in climate policy large losses in consumption have to be weighted against large damages from climate change. In addition much mitigation costs borne today and here, while damages occur in other parts of the world and in the far future. These trade-offs involve fundamental ethical questions and the whole society must have a chance to participate in this debate. While democratic procedures are imperfect, under climate policy independence such a process is totally lacking.

Levy (1998) identifies two prerequisites for CBI to be in line with democracy:

1. "Monetary policy actions have narrow consequences; they affect price stability and the soundness of the financial system but do not involve social tradeoffs."
2. "The central bank has a systematic, objective method of selecting the right policy to meet its goal of a stable currency and a healthy financial sector".

While these conditions are under debate in monetary policy, for climate policy they are surely not fulfilled. It *does* involve deep social trade-offs and there is *no* undisputed way to determine the right amount of emission reductions (as the Nordhaus-Stern discrepancy shows).

To sum up, I believe it is hard to find institutional designs that solve the time inconsistency problem in climate policy. Furthermore, a carbon bank seems to violate fundamentally the democratic idea of societies determining the right policy for themselves. There are three questions, "Can a carbon bank be set up?", "Is it a solution to time inconsistency?", and "Do we want to pay the price in terms of loss of democratic control?". For the first question, I think the answer is "yes". For the second and the third question, the answer is probably much closer to "no" for climate policy than for monetary policy.

Delegation of Monitoring and Advice

Letting an autonomous institution determine the tax rate or the cap is the strongest form of delegation and the *ultima ratio* in terms of polity-based commitment devices. A softer form is to establish an independent institution for monitoring and advice. This is maybe the role the UK Committee on Climate Change can play in the long run. While the CCC has no possibility to directly conduct policy, it can overview governmental and parliamentarian actions and check if they are in line with proposed climate targets. Its weapon is not direct power, but pressuring policy-making institutions through the public opinion. Such a monitoring institution makes especially sense in combination with a legal climate target (see below).

7.2 Carbon Pricing: Policy

Much less attention than the institutional design of policy has been attracted by the fact that not only polities, but also policies vary according to their degree of dynamic consistency. Some policies are more credible than others.

Time inconsistency emerges in my model because the government is not able to guarantee the future tax rate on carbon, or, equivalently the future cap in a cap and trade system. Firms underinvest in low-carbon technologies because they fear (rationally) the government is going to lower carbon taxes once investments are sunk, making the recovery of investment costs impossible. In other words: Firms fear future expropriation through a *reduction* of the carbon price. Can carbon pricing policies be modified to make future price reductions less probable?

Put Options for Permits

Ismer and Neuhoff (2009) propose to establish a floor (minimum) price for carbon permits in a cap and trade system through issuing put options on emission permits. Put options establish the right, but not the obligation, to sell permits back to the government at a certain strike price.

Put options prevent the carbon price to fall below the strike price. However, they don't prevent the price to fall all the way down to the strike price. In other words, they can prevent the most severe consequences of time inconsistency, but they cannot prevent all downward bias. If the commitment price would be $30, and the consistent price is $5, a strike price of $10 would save the price from falling all the way down to $5, but it sill would slump from $30 to $10.

Put options are only feasible in a cap and trade system, not for a carbon tax.

Prices vs. Quantities

In my model there is no difference between a carbon tax and a cap and trade system. The time inconsistency mechanism that I identify affects price regulation as much as quantity regulation. Other sources of time inconsistency affect only cap and trade system. Baldursson and von der Fehr (2008) argue that in a cap and trade system the regulator has an incentive to increase the supply of permits over time, such as the seller of a durable good has an incentive to sell more and more that that good.

This problem could be solved by replacing the cap and trade system by a carbon tax.

A Legal Emission Target

The Climate Change Act became law in 2008. It makes it the duty of the Secretary of State to ensure that the UK GHG emissions for the year 2050 are at least 80% lower than in 1990. Such a legally binding emission target can serve as a commitment device. An independent monitoring institution, as discussed above, can overview policies to check if they are in line with the overall target. If government fails to meet intermediate targest, under the UK law it is obligated to justify herself in a public report and explain how it plans to return to the reduction path. The "emission target with monitoring institution" lies somewhere between polity- and policy-based commitment.

7.3 Substitute Carbon Pricing

If carbon-pricing policies fail to be sufficiently consistent, it could make sense to replace them by other types of policies. With other policies, it is easier to establish credibility, if these policies cannot be reversed easily. These policies are more credible and less prone to time inconsistency. On the other side, these policies are generally not an efficient way to mitigate GHG emissions. As a consequence, there is a trade-off between static efficiency and time consistency.

Alternative policies include feed-in tariffs for renewable electricity, research subsidies for low-carbon goods, carbon contracts, and command and control policies.

Feed-In Tariffs

Feed-in tariffs for electricity from renewable resources such as the German "Erneuerbare Energien Gesetz" (EEG) guarantee the producer of renewable energy a minimum price over a certain time span. For example, for a small photovoltaic module installed in 2009 on a roof top, the EEG guarantees 43 Cent per kwh over the next 20 years. More than half of all EU member countries have adopted such feed-in tariffs.

In a static, neoclassical analysis feed-in tariffs make little sense if there is already a cap and trade system installed (Walz 2005, Frondel and Schmidt 2006). The idea of a cap and trade system (or a carbon tax) is to find the cheapest mitigation options through a decentralized market. Feed-in tariffs, especially with technology- and location-specific subsidies, imply that the government favors one mitigation option over the other. Under a cap and trade system *only* the cap determines total GHG emissions. In a static setting, feed-in tariffs are costly without reducing emissions at all.

Taking time inconsistency into account results in a different picture. The EEG gives investors the legal security and a claim of property rights towards the government, to receive the same subsidy for 20 years. This subsidy cannot be reversed easily.

Research Subsidies

Authors like Abrego and Perroni (2002) and Montgomery and Smith (2005) propose to subsidize the research and development of low-carbon technologies to substitute or complement carbon pricing as principle climate policy. Research subsidies are paid upfront, thus they cannot be time inconsistent by definition. Research subsidies have, however, other disadvantages. Most importantly, the state has to decide in advance which technology and which research team should be supported. On the one hand, this information is very hard to obtain and markets are probably much more capable to collect the decentralized information than central decision makers. On the other hand, given the information asymmetry between the government and researchers, moral hazard and adverse selection problems are abundant. Even if these informational issues could be overcome, research subsidies are a solution for the invention process, but not for the adaption and diffusion process of innovation. A big advantage of carbon pricing policies is that they promote the application of today's existing low-cost mitigation option.

Carbon Contracts

Helm and Hepburn (2005) propose a mechanism to overcome some of the information problems with research subsidies. The proposed “Carbon Contract” is conceptionally similar to Kremer's (1998) randomized patent auction. According to Helm and Hepburn's idea, the government seeks to buy a certain amount of emission reductions at the lowest price. Companies bid their prices, and the government writes contracts with those firms who supply a future stream of reductions at the lowest costs. These contracts establish property rights.

However, similar to offset mechanisms like the Clean Development Mechanism, the carbon contract depends on business-as-usual scenarios. “A certain amount of reductions” means that actual reductions are below the value they would have been without the contract by that same amount. This logically requires forecasts of the business as usual emission path. Such forecasts are inherently difficult to establish, especially in the context of changing technology and over long time horizons, as the fierce debate on the Clean Development Mechanisms confirms.

7.4 The Role of Property Rights

Instruments such as put options, feed-in tariffs, or research subsidies are more credible, because they cannot changed easily ex post. Carbon pricing through a carbon tax or a cap and trade system can be changed more easily ex post. While this is far from being a final judgment, I an interpretation why this is the case.

Economically, giving a positive payment for doing something is equivalent to requesting a negative payment for not doing it. In both cases the opportunity costs of the action are the same. Legally, it seems to me that there is a difference.

Carbon pricing instruments, a tax a quantity restriction, induce mitigation by announcing that emissions will cost something in the future. Instruments such as subsidies induce mitigation by announcing that reducing emissions with be rewarded in the future. The legal system in western countries seems to be able to prevent deflection from the latter promise, but not from the former.

Why is there a legal difference where economically there seems to be none? I believe the reason is the legal tradition of property rights. In most OECD countries property rights have been defended highly successfully against expropriation over the last two centuries. Laws and court decisions have span a fine cobweb of legal barriers against authoritarian intervention in property rights (North and Weingast 1989).

This legal tradition can be used to build commitment. Policies that create enforcible property rights are more credible than others. While the current legal system in western countries does not protect investors from lowering the tax rate, it does protect them from lowering subsidies. I have the right to receive contractually established payments from the government, and courts generally will enforce this right. But no contracts exists that establish the right to have my competitors taxes.

In addition, in instruments that create a market, regulation is complex, and any change in regulation affects all stakeholder of the market. For example, in a carbon cap and trade system myriads of regulatory decisions have to be made: How are new plants counted? What are the rules for importing certificates? How are newly entering sectors treated? How are other greenhouse gases converted to CO_2e? What estimation methodologies are used for determining emissions? The list is endless. Any of there decision affects *all* agents that are regulated in the market. This necessarily means that if policy makers want to reduce the price of carbon due to time inconsistency, it is easy to find a way to do it. They don't have to expand the total cap, but simply to make the import of allowances easier. Or to count natural sinks. Or to use a more conservative estimation methodology.

Subsidy policies such as feed-in tariffs can also be adjusted, and this is indeed done regularly. But such changes affect *future* investors only. Once investments are made, the rules for feed-in tariffs cannot be changed anymore. The reason is of course that investors have obtained a claim of property rights.

I believe policy that establish property rights are more credible than others. The reason is not economical or political, but rather legal. Carbon pricing instruments, the most efficient policies for GHG abatement, usually do not establish property rights, since they transfer money from firms to the government and not the other way round. Subsidies, in contrast, establish property rights and are more credible. They can have the form of, e.g., research subsidies, carbon contracts, and feed-in tariffs.

8 Concluding Remarks

Modeling Results

The analytical model of the electricity market under carbon taxation outlined in section 6 yields several important results with respect to the optimal tax level, the necessary condition for time inconsistency, and the direction of the time inconsistency bias.

1. Taking public finance aspects into account, the optimal carbon tax is larger than the Pigouvian tax rate.
2. If, and only if, investment decisions in fixed capital are influenced by carbon taxation, time inconsistency arises.
3. If investment responds positively on carbon taxation, and public finance plays little role, time inconsistency causes a downward bias on carbon taxes. Climate policy is less stringent than it should be.
4. Under a Cobb-Douglas specification, investments respond positively on carbon taxes if, and only if, the price elasticity of demand is smaller than unity in absolute value, which seems to be the case empirically.
5. Due to the downward bias of the tax, final energy consumption is too high compared to the welfare optimum, emissions are too high, and investment is too low.

There is an important and clear policy recommendation from these findings: The danger is that climate policy is too lax. Policy should be designed in a way that prevents softening.

Results Regarding Commitment Devices

Polity-based commitment devices such as delegation seem to work quite well in monetary policy. Because time horizons are several dimensions larger in climate policy than in monetary policy, delegation probably is much more difficult in climate policy. Given the large uncertainty about the optimal amount of mitigation, specifying a clear and transparent emission target for climate policy is not feasible. Also democracy-theoretic considerations argue against a carbon bank.

Policy-based commitment devices seem to be much more promising. Especially policy that establish property rights are somewhat shielded from being watered down ex post and consequently are more credible. Feed-in tariffs are a prominent example of property-right establishing policy in electricity markets. Research subsidies are similarly credible.

Future Modeling Research

In the following I want to outline possible direction of future research. In analytical models of time inconsistency in climate policy several features of the electricity markets should be taken into account for more realistic modeling.

Most important, electricity markets are highly concentrated. Electricity is not tradeable on world markets and generation exhibits significant economies of scale. Taken together this results in significant market power. Thus regulated firms can influence the price and they also can invest strategically: For example, they could underinvest strategically in abatement technologies, increasing the pressure on politics to deviate from targets and soften climate policy. Following this line of thinking, introducing market power would make time inconsistency stronger and lead to a stronger downward-bias on carbon taxes.

Another important issue is to include a more generalized production function. In a first step the Cobb-Douglas production technology could be replaced by a constant elasticity of substitution (CES) production function. My intuition is that the better capital and fossil fuels can be substituted, the stronger the effect of time inconsistency is. If capital can easily replace coal then it makes a large difference if capital is sunk or not. If it can hardly replace any coal, there is no big difference ex post from ex ante. My guess is that capital and fuels are very well substitutes if a long time horizon is under consideration. Since electricity can even be relatively easily produced without any emissions, the substitutability might be nearly perfect. As a consequence, using a calibrated CES function would probably make time inconsistency more severe.

Finally, heterogeneous households should be introduced to understand the consequences of carbon taxation on income distribution and the effect of income distribution on time inconsistency. This issue has perhaps less priority since it has been already discussed in the literature. Nevertheless I believe much remains to be learned. If energy taxes are regressive, and government has an interest to flatten the income distribution, there is yet another reason to lower taxes ex post. My intuition is that introducing heterogeneous households makes the time inconsistency stronger.

To sum up, I regard my analytical model as highly stylized. Many important characteristics of the final energy market are missing. I also believe it is pretty conservative. A more realistic model would probably lead to even stronger time inconsistency problems.

Future Research on Commitment Devices

Also with respect to commitment devices much research remains to be done. I believe a more systematic and rigorous investigation of different policies, their exposition to time inconsistency, and the reasons for that variance is highly needed. My ideas with respect to the role of property rights as commitment devices and the possibility to establish property right claims through climate policy are still very preliminary. Joint research with an expert in law is highly warranted.

A second line of important future research on commitment is the question of how much commitment is wanted at all if there is uncertainty. In the present work uncertainty played very little role. In fact, uncertainty is pervasive in climate policy, and learning takes place at a high speed. Most probably there is a trade-off between commitment (to combat time inconsistency) and flexibility (to adjust to new information). How conditional property rights could be a solution to this problem remains to be investigated.

References

Abrego, Lisandro and Carlo Perroni, "Investment subsidies and time-consistent environmental policy," *Oxf. Econ. Pap.*, October 2002, *54* (4), 617–635.

Acemoglu, D., "Why not a political Coase theorem? Social conflict, commitment, and politics," *Journal of Comparative Economics*, December 2003, *31* (4), 620–652.

Alesina, Alberto and Lawrence H. Summers, "Central Bank Independence and Macroeconomic Performance: Some Comparative Evidence," *Journal of Money, Credit and Banking*, 1993, *25* (2), 151–162.

Atkinson, A. B. and N. H. Stern, "Pigou, Taxation and Public Goods," *The Review of Economic Studies*, 1974, *41* (1), 119–128.

Baldursson, Fridirik and Nils-Henrik von der Fehr, "Prices vs. quantities: Public finance and the choice of regulatory instruments," *European Economic Review*, October 2008, *52* (7), 1242–1255.

Barro, Robert and David Gordon, "A Positive Theory of Monetary Policy in a Natural Rate Model," *The Journal of Political Economy*, 1983, *91* (4), 589–610.

Berger, Helge, Jakob de Haan, and Sylvester Eijffinger, "Central Bank Independence: An Update of Theory and Evidence," *Journal of Economic Surveys*, 2001, *15* (1), 3–40.

Berman, Sheri and Kathleen Mcnamara, "Bank on Democracy," *Foreign Affairs*, March 1999, *78* (2).

Biglaiser, Gary, John K. Horowitz, and John Quiggin, "Dynamic pollution regulation," *Journal of Regulatory Economics*, July 1995, *8* (1), 33–44.

Bovenberg, Lans A. and Ruud A. de Mooij, "Environmental Levies and Distortionary Taxation," *The American Economic Review*, 1994, *84* (4), 1085–1089.

Buchner, Barbara K., Carlo Carraro, and A. D. Ellerman, "The Allocation of European Union Allowances: Lessons, Unifying Themes and General Principles," *Social Science Research Network Working Paper Series*, September 2006.

Bulow, Jeremy I., "Durable-Goods Monopolists," *The Journal of Political Economy*, 1982, *90* (2), 314–332.

Calvo, Guillermo, "On the Time Consistency of Optimal Policy in a Monetary Economy," *Econometrica*, 1978, *46* (6), 1411–1428.

Camba-Mendez, Gonzalo, Juan Á. García, and Diego R. Palenzuela, *Relevant economic issues concerning the optimal rate of inflation*, European Central Bank,

Carr, E. H., *The Twenty Years' Crisis': 1919-1939*, New York: Perennial, 1939.

Coase, Ronald, "The Problem of Social Cost," *The Journal of Law and Economics*, January 1960, *3* (1), 1+.

——, "Durability and Monopoly," *Journal of Law and Economics*, 1972, *15* (1), 143–149.

Cukierman, Alex, Steven B. Webb, and Bilin Neyapti, "Measuring the Independence of Central Banks and Its Effect on Policy Outcomes," *World Bank Economic Review*, September 1992, *6* (3), 353–98.

D'artigues, Agnes, Jacques Percebois, and Thierry Vignolo, "The time-inconsistency of alternative energy policy," *Economics Bulletin*, 2007, *1* (1), 1–7.

Dehaan, J., D. Masciandaro, and M. Quintyn, "Does central bank independence still matter?," *European Journal of Political Economy*, December 2008, *24* (4), 717–721.

Edenhofer, Ottmar, Brigitte Knopf, and Matthias Kalkuhl, "CCS: CO2-Sequestrierung: Ein wirksamer Beitrag zum Klimaschutz?," *Ifo-Schnelldienst*, March 2009, *03/2009.*

——**, Robert Pietzcker, Matthias Kalkuhl, and Elmar Kriegler**, "Taxation instruments for reducing greenhouse gas emissions, and comparison with quantity instruments," March 2009.

Elgie, Robert, "Democratic accountability and central bank independence: Historical and contemporary, national and European perspectives," *West European Politics*, 1998, *21* (3), 53–76.

Espey, James A. and Molly Espey, "Turning on the Lights: A Meta-Analysis of Residential Electricity Demand Elasticities," *Journal of Agricultural and Applied Economics*, April 2004, *36* (01).

Fischer, Stanley, "Dynamic inconsistency, cooperation and the benevolent dissembling government," *Journal of Economic Dynamics and Control*, 1980, *2* (2-4), 93–107.

—— **and Franco Modigliani**, "Towards an understanding of the real effects and costs of inflation," *Review of World Economics*, December 1978, *114* (4), 810–833.

Frondel, Manuel and Christoph Schmidt, "Emissionshandel und Erneuerbare-Energien-Gesetz: Eine notwendige Koexistenz?," *RWI: Positionen*, May 2006, *10.*

Gallini, Nancy and Suzanne Scotchmer, "Intellectual Property: When Is It the Best Incentive System?," *Innovation Policy and the Economy*, 2002, *2*, 51–77.

Goulder, L., I. Parry, R. Williamsiii, and D. Burtraw, "The cost-effectiveness of alternative instruments for environmental protection in a second-best setting," *Journal of Public Economics*, June 1999, *72* (3), 329–360.

Goulder, Lawrence H., "Environmental taxation and the double dividend: A reader's guide," *International Tax and Public Finance*, August 1995, *2* (2), 157–183.

Harberger, Arnold C., "The Measurement of Waste," *The American Economic Review*, 1964, *54* (3), 58–76.

Heal, Geoffrey, "Climate Economics: A Meta-Review and Some Suggestions for Future Research," *Rev Environ Econ Policy*, December 2009, *3* (1), 4–21.

Helm, Dieter and Cameron Hepburn, "Carbon contracts and energy policy: an outline proposal," Technical Report 2005.

___ , ___ , and Richard Mash, "Credible Carbon Policy," *Oxford Review of Economic Policy*, September 2003, *19* (3), 438–450.

___ , ___ , and ___ , "Time-Inconsistent Environmental Policy And Optimal Delegation," Technical Report 14, Royal Economic Society 2004.

Hicks, J. R., "Mr. Keynes and the "Classics"; A Suggested Interpretation," *Econometrica*, 1937, *5* (2), 147–159.

Houghton, R. A., "Why are estimates of the terrestrial carbon balance so different?," *Global Change Biology*, 2003b, *9* (4), 500–509.

IPCC, *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment*, IPCC, 2007a.

___ , *Climate Change 2007: The Physical Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2007b.

___ , *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2007c.

___ , *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2007d.

Ismer, Roland and Karsten Neuhoff, "Commitments through financial options: An alternative for delivering climate change obligations," *Climate Policy*, 2009, *9* (1), 9–21.

Jacome, L. and F. Vazquez, "Is there any link between legal central bank independence and inflation? Evidence from Latin America and the Caribbean," *European Journal of Political Economy*, December 2008, *24* (4), 788–801.

Kennedy, Peter W. and Benoit Laplante, "Environmental policy and time consistency - emissions taxes and emissions trading," Policy Research Working Paper Series 2351, The World Bank May 2000.

Keynes, John M., *The General Theory of Employment, Interest and Money*, Macmillan, 1936.

Kremer, Michael, “Patent Buyouts: A Mechanism for Encouraging Innovation,” *The Quarterly Journal of Economics*, 1998, *113* (4), 1137–1167.

Kydland, Finn and Edward Prescott, “Rules Rather than Discretion: The Inconsistency of Optimal Plans,” *The Journal of Political Economy*, 1977, *85* (3), 473–492.

Laffont, Jean-Jaques and Jean Tirole, “Pollution permits and environmental innovation,” *Journal of Public Economics*, October 1996, *62* (1-2), 127–140.

Lenton, Timothy M., Hermann Held, Elmar Kriegler, Jim W. Hall, Wolfgang Lucht, Stefan Rahmstorf, and Hans J. Schellnhuber, “Tipping elements in the Earth’s climate system,” *Proceedings of the National Academy of Sciences*, February 2008, *105* (6), 1786–1793.

Levine, Paul, John Stern, and Francesc Trillas, “Utility price regulation and time inconsistency: comparisons with monetary policy,” *Oxford Economic Papers*, July 2005, *57* (3), 447–478.

Levy, David T., “Does an Independent Central Bank Violate Democracy?,” *Social Science Research Network Working Paper Series*, March 1998.

Lipsey, R. G. and Kelvin Lancaster, “The General Theory of Second Best,” *The Review of Economic Studies*, 1956, *24* (1), 11–32.

Lucas, Robert E., “On the welfare cost of inflation,” Working Papers in Applied Economic Theory 94-07, Federal Reserve Bank of San Francisco 1994.

Mankiw, Gregory N., “Small Menu Costs and Large Business Cycles: A Macroeconomic Model of Monopoly,” *The Quarterly Journal of Economics*, 1985, *100* (2), 529–537.

Marsiliani, Laura and Thomas I. Renström, “Time Inconsistency in Environmental Policy: Tax Earmarking as a Commitment Solution,” *The Economic Journal*, 2000, *110* (462), 123–138.

Montgomery, David and Anne Smith, “Price, Quantity, and Technologiy Strategies,” Technical Report, Charles River Associates 2005.

Montgomery, David W., “Markets in licenses and efficient pollution control programs,” *Journal of Economic Theory*, December 1972, *5* (3), 395–418.

Morgenthau, Hans, *Politics Among Nations: The Struggle for Power and Peace*, New York: Alfred A. Knopf, 1948.

Newell, Richard and William Pizer, “Discounting the distant future: how much do uncertain rates increase valuations?,” *Journal of Environmental Economics and Management*, July 2003a, *46* (1), 52–71.

Niskanen, William A., *Bureaucracy and Representative Government*, 1st pbk. print ed., AldineTransaction, March 2007.

Nordhaus, William, *A Question of Balance. Weighing the Options on Global Warming Policies*, Yale University Press, 2008.

—— **and Joseph Boyer**, *Warming the World: Economic Models of Global Warming*, MIT Press, 2000.

North, Douglass C. and Barry R. Weingast, "Constitutions and Commitment: The Evolution of Institutional Governing Public Choice in Seventeenth-Century England," *The Journal of Economic History*, 1989, *49* (4), 803–832.

Pigou, A. C., *A Study in Public Finance*, Macmillan, 1928.

Robock, Alan, "20 reasons why geoengineering may be a bad idea," *Bulletin of the Atomic Scientists*, May 2008, *64* (2).

Rogoff, Kenneth, "The Optimal Degree of Commitment to an Intermediate Monetary Target," *The Quarterly Journal of Economics*, 1985, *100* (4), 1169–1189.

Romer, Paul M., "Endogenous Technological Change," *The Journal of Political Economy*, 1990, *98* (5), S71–S102.

Samuelson, Paul, "Economics. An Introductory Analysis.," 1948.

Solow, Robert M., "A Contribution to the Theory of Economic Growth," *The Quarterly Journal of Economics*, 1956, *70* (1), 65–94.

Sprinz, Detlef, *Long-Term Policy Problems: Definition, Origin, and Responses.*, The University of Michigan Press, 2008.

Stern, Nicholas, *The Economics of Climate Change: The Stern Review*, Cambridge University Press, January 2006.

Stiglitz, J. E. and P. Dasgupta, "Differential Taxation, Public Goods, and Economic Efficiency," *The Review of Economic Studies*, 1971, *38* (2), 151–174.

Symons, Elizabeth, Stefan Speck, and J. Proops, "The Effects of Pollution and Energy Taxes across the European Income Distribution," Keele Department of Economics Discussion Papers (1995-2001) 2000/05, Department of Economics, Keele University 2000.

Tol, Richard, "Estimates of the Damage Costs of Climate Change. Part I: Benchmark Estimates," *Environmental and Resource Economics*, January 2002a, *21* (1), 47–73.

Walz, R., "Interaktion des EU Emissionshandels mit dem Erneuerbare Energien Gesetz," *Zeitschrift für Energiewirtschaft*, 2005, *29* (4).

Weber, Max, *Wirtschaft und Gesellschaft* 1922.

Weitzman, M., "Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate,," *Journal of Environmental Economics and Management*, November 1998, *36* (3), 201–208.

Weitzman, Martin L., "Prices vs. Quantities," *The Review of Economic Studies*, 1974, *41* (4), 477–491.

World Bank, ed., *Argentina: From Insolvency to Growth*, Washington DC: The World Bank, 1993.

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