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The MARKAL-MACRO Model and the Climate Change

S. Kypreos

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Contents

1	Introduction	3
2	The Basic Relations of the Model	4
2.1	The Basic Equations of the MACRO submodel	5
2.2	Profit Maximization and Demand Functions	7
2.2.1	Benchmarking the production function	9
2.2.2	How MARKAL-MACRO works	9
2.3	Some final remarks	10
2.3.1	Elasticity of substitution	10
2.3.2	The demand decoupling factor, DDF	12
3	Economic Implications of Environmental Policy	14
3.1	Scope of the study	14
3.2	Main Assumptions	15
3.3	Scenarios and Emissions	16
4	Main Results	17
4.1	Primary Energy	17
4.2	Shares of Fossil, Nuclear and Renewable Energy	17
4.3	Final Energy	20
4.4	Electricity Production	20
4.5	Carbon Tax and Economic Implications	20
4.6	CO ₂ Reduction by Technology and Price Effects	22
5	Asking for Efficient Policies	24
5.1	Trade-offs between CO ₂ and other GHGs	24
5.2	A Tax-Compensation Approach	24
5.3	International Cooperation	26
6	Stochastic Analysis	28
6.1	Mathematics and Terminology	28
6.2	Hedging strategy with MARKAL	31
6.3	Conclusions	33
6.3.1	Deterministic analysis	33
6.3.2	Stochastic analysis	34
7	Appendix A: The MARKAL Stand-alone Model	36
7.1	Summary	36
7.2	Indexes, variables and equations	36
7.2.1	Indexes	37
7.2.2	Model variables	38
7.2.3	Description of equations	39
7.3	Emission and material balances	44
7.4	The objective functions of the model	45
7.5	Multi objective analysis	47
7.6	The pass-out turbines	49

8	Appendix B: Sensitivity Analysis	50
8.1	Scenarios analyzed with the US data base	50
8.1.1	Autonomous efficiency improvement, AEEI	50
8.1.2	Elasticity of substitution	52
8.1.3	High conservation potential	55
8.2	Conclusions on sensitivity	56
9	Appendix C: Partial equilibrium	57
9.1	Introduction	57
9.2	The PIES algorithm	58
10	References	61

1 Introduction

The climate change policy analysis introduces new challenges to the energy modeling community.¹ This is because an effective CO_2 mitigation policy requires the establishment of price regimes by a few factors above our experience. This is necessary in order to restructure the energy economy, which is now based on low price fossil fuels, and introduce, in the longer term, carbon-free energy sources. The challenge for the energy modeling is to show how the shift towards non-carbon fuels can be obtained and to identify **efficient** and simultaneously **equitable** policy options. Thus, the models used in the past to analyze the energy systems, based for example on inelastic energy demand approximations, are not anymore sufficient.

For this reason a family of models has been developed called Markal-Macro (MM). The development of MM opens new options for the energy community. Now, not only that we have the flexibility to adjust demands to price changes but we can also estimate the economic implications of environmental or supply constraints (e.g., CO_2 , NO_x , nuclear availability, extensive use of renewables etc.). The use of MARKAL-MACRO though, is associated with extra complexity and new challenges. We should understand better the energy to economy relations and the demand/supply interactions for using properly the model.

The project became feasible due to the pioneering work of Profs. A. Manne and C.-O. Wenne [1992]. The contribution of G. Goldstein, [1991] integrating the software in his MUSS system and his data-base support is also significant. My contribution to the MM project begins in 1992 and it is related to the development of procedures that help to specify some model parameters, or calibrate the model to some pre-specified sectorial demand projections for the reference case. The development of the partial equilibrium version of Markal, and of the MM-trade is done together with other project participants. Also, the early application of the model and its critical review has helped to clarify the model ability to perform greenhouse policy studies.

We can claim now that: **The model MARKAL-MACRO and its extensions, is appropriate to study partial and general equilibrium in the energy markets and the implications of the carbon dioxide mitigation policy. The main advantage of MM is the explicit treatment of energy demand, supply and conversion technologies, including emission control and conservation options, within a general equilibrium framework.**

The famous gap between top-down and bottom up models is resolved and the economic implications of environmental and supply policy constraints can be captured either in an aggregated (Macro) or in a sectorial (Micro) level. The multi-regional trade version of the model allows to study questions related to efficient and equitable allocation of cost and benefits associated with the climate change issue. Finally, the stochastic version of the model allows to assess policies related to uncertain and even catastrophic effects and define appropriate hedging strategies.

The report is divided in three parts:

- The first part gives an overview of the new model structure, it describes its macro economic part and explains its calibration.
- The second part refers to the model application for Switzerland when analyzing the economic implications of curbing CO_2 emissions or policies related to the introduction of a carbon tax,

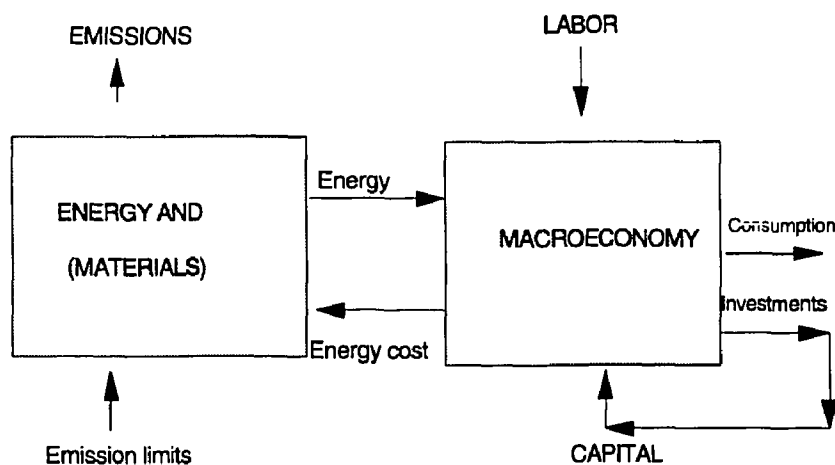
¹The report is the Swiss contribution to the IEA/OECD Energy Technology Systems Analysis Project (ETSAP), Annex V called **Energy options for sustainable development: Technological solutions, economic impacts and emission reduction strategies**, 1993-1995.

including a hedging strategy.

- The last part is organized in form of Appendices and gives a mathematical description and some potential extensions of the model. It describes also a sensitivity analysis done with MARKAL-MACRO in 1992 [Kypreos, 1992].

2 The Basic Relations of the Model

Markal-Macro is actually a “model invention” which defines the interactions between the economy and the energy system under a set of environmental constraints. There are some new basic relations introduced in the model on the top to the Markal equations to be described in the following chapter.



overmm.qpr

Fig. 1: Overview of the MARKAL-MACRO submodel

The primary inputs capital, labor, and energy generate the economic output which is distributed to consumption, investments and energy requirements and for satisfying the environmental limitations (by restructuring the energy subsystem). The energy submodel is an explicit engineering model that includes conservation options and technological change.

2.1 The Basic Equations of the MACRO submodel

MARKAL-MACRO defines the interactions between the economy and the energy system under a set of environmental constraints. There are some new constraints introduced in the MACRO submodel on the top of the equations of MARKAL, necessary to drive the macroeconomic growth and to link the economic activities to the energy system. The new variables and constraints are: consumption C , investments I , labor L , capital K , energy cost EC , and the demands for energy services D_m . Markal is a process oriented engineering model that describes all energy transformations from primary sources to energy services. It uses as variables the resources of the energy system, the installed capacity and investments on new technologies and the flow of energy through the different technologies. Exogenous model parameters are the fuel prices, the resource availability and the potential economic growth. It follows a list of the most important MACRO constraints:

- **The utility function UTIL:**

The model maximizes a utility function which is defined as the integral of the discounted logarithm of consumption, where r is the time preference rate for discounting utility.²

$$U = \int_0^T \ln C_t \cdot e^{-rt} dt \quad (1)$$

The integral is approximated assuming T periods of time duration δt and a terminal condition for the time period afterwards. Notice that r becomes a function of time (r_k).

$$UTIL = \sum_{t=1}^{t=T-1} \beta_t \ln C_t + \frac{\beta_T \ln C_T}{1 - (1 - r)^{\delta t}} \quad (2)$$

while

$$\beta_t = \prod_{k=0}^{k=t-1} (1 - r_k)^{\delta t} \quad (3)$$

- **The production function PROD:**

A constant elasticity of substitution (CES) function describes the “Gross Output” Y , of the economy, as function of the primary inputs. The aggregate production function (primal) of the economy takes the form,

$$Y_t = [a \cdot K_t^{\rho(1-\alpha)} \cdot L_t^{\rho(1-\alpha)} + \sum_m b_{mt} \cdot D_{mt}^{\rho}]^{1/\rho} \quad (4)$$

and links the primary input requirements of the economy capital K , and labor L , with the intermediate inputs of demands D_m , (a and b_m are scaling factors to be specified through the calibration of the model). The CES production function allows substitution between the pair capital-labor and the energy services when the relative prices change. The elasticity of substitution³ is $\sigma = 1/(1 - \rho)$

² The issue of discounting is one of the most critical problems in the CO_2 debate since the expected damages will take place in the second half of the next century and their present worth value is low. Discounting is less critical in our model since we don't specify optimal policy based on cost/benefit analysis.

³ If $Z = f(x, y)$ is a production function and x, y are the factors of production then, the elasticity of substitution σ , describes how to production factors substitute each other. σ is defined as the relative change of the ratio $\frac{x}{y}$ to the relative change of the marginal rate of substitution among these factors. The marginal rate of substitution now

- **The USE of output function:**

The “Gross Output” is consumed C , or used for investments I , and for meeting the financial requirements of the energy sector EC . The energy cost EC , is estimated in MARKAL by an explicit description of the energy sector including options to protect the environment. The basic identity that defines the use of Gross Output Y is:

$$Y_t = C_t + I_t + EC_t$$

If the energy price increases, due to resource depletion or environmental constraints then, energy is substituted by capital and labor (CES production function), while the output Y and the demand for energy services are decreasing. This equation assumes that the gross domestic product is given as the summation of consumption and investments and thus the net exports are balanced.⁴

- **The capital formation function, CAP:**

Depreciation of existing capital and new investments specify the accumulation of the production factor capital as follows:

$$K_t = (1 - \delta k)^{\delta\tau} K_{t-1} + \delta\tau/2 \cdot [(1 - \delta k)^{\delta\tau} \cdot I_{t-1} + I_t] \quad (5)$$

δk is the annual depreciation factor, and $\delta\tau$ is the time length (i.e. years) per period. Labor is exogenous and it is expressed in effective units relative to the starting year.

- **The terminal conditions, TC:**

The equation is applied after the end of the time horizon to ensure that the rate of investments provides for depreciation dr , and the net growth of capital gr :

$$K_T \cdot (gr + dr) \leq I_T \quad (6)$$

- Non-linear market penetration penalty functions that help to avoid extreme penetration rates of technologies.

Two are the basic constraints coupling MACRO to MARKAL, the demand for energy services and the energy cost (See also Appendix A for Markal):

- **The demand constraints:**

They couple the MARKAL end-use devices Z , with the adjusted MACRO demand for energy services DM' : ddf are exogenous demand decoupling factors that could represent, among others, annual rates of efficiency improvement

$$\sum_{d^m=1}^{D^m} Z_{d^m t} \geq DM'_{mt} = D_{mt} \cdot e^{-ddf \Delta t} \quad (7)$$

is, $R(x, y) = -\frac{dy}{dx} = \frac{f'_y}{f'_x}$, e.g., the slope of the production function at the isoquant (for $dz = 0.0$). It can be shown that if the production function is homogeneous of degree one then, the output increases proportional to the increase of the inputs and thus we have “constant returns to scale”. In the case of a constant elasticity of substitution (CES) function, as the one used in MM, we have: $\sigma = \frac{\partial \ln(x/y)}{\partial \ln R(x/y)} = \frac{\partial \ln(x/y)}{\partial \ln(P_y/P_x)}$, it will be shown that $\sigma = 1/(1 - \rho)$

⁴The Markal-Macro multi-regional model introduces trade and treats exports-imports as endogenous model variable.

- **The energy system cost: EC**

The annualized energy system cost is expressed using the variables of MARKAL. Some terms are shown below: the parameter sc_{rt} is the specific investment cost per unit of capacity while cr_{rt} is the annualized capital recovery factor per technology. If Y represents new capacity investments and W the resource use then we have:

$$\begin{aligned}
 EC_t = & \sum_r Y_{rt} \cdot sc_{rt} \cdot cr_{rt} && \text{annualized capital cost} \\
 & + \sum_{sjk} p_{sjkt} \cdot W_{sjkt} && \text{resource cost} \\
 & + \dots \text{other costs like fuel, etc.}
 \end{aligned}
 \tag{8}$$

The advantage of MM is that the demand for energy services is an endogenous model variable that appears in the production function. The dual equation of the production function, which is estimated as a first order optimality condition for maximizing utility, defines the demand for energy services as function of shadow prices and of the aggregate economic activity. The energy supply function is estimated in Markal and defines the marginal cost of energy services. Demand and supply of energy services are balanced to clear the energy markets and define the equilibrium price of energy. This equilibrium is satisfied as optimality condition in the model without the need to use an iterative approach. Thus, Markal-Macro is formulated as a non-linear mathematical programming (MP) problem which is solved directly. It is a “look-ahead” rather than a “recursive dynamic” model.

2.2 Profit Maximization and Demand Functions

We first consider a simple version of the production function in order to derive the demand function of Markal-Macro. In this simple version the production factors labor, capital and energy services are represented by aggregate variables.

Assume that V represents the value added by capital and labor, E the energy input to the economy, Y the economic output and P_x the price of x .

The model that maximizes utility maximizes also the profit function. The profit function equals the value of production minus the production cost. The **profit function** to be maximized is:

$$\pi = Y * P_y - V * P_v - E * P_e \tag{9}$$

that subjects to the production constraint:

$$Y = [a * V^\rho + b * E^\rho]^{1/\rho} \tag{10}$$

Using the Lagrange function of the problem defined above:

$$\Lambda = \pi - Y * P_y + V * P_v + E * P_e + \lambda * [Y - (a * V^\rho + b * E^\rho)^{1/\rho}] \tag{11}$$

and setting all the partial derivatives to zero, we get:

$$P_v = P_y * a(Y/V)^{1-\rho} \tag{12}$$

$$P_e = P_y * b(Y/E)^{1-\rho} \quad (13)$$

or the equivalent relations defining the demand for energy and the economic activity as function of their prices:

$$E = Y * (P_e/bP_y)^{-1/(1-\rho)} \quad (14)$$

$$V = Y * (P_v/aP_y)^{-1/(1-\rho)} \quad (15)$$

These demand relations are implicitly imposed when solving for Markal-Macro maximizing the utility function of the model. The elasticity of substitution can be estimated based on the relations above; we have:

$$\frac{E}{V} = \left[\frac{P_e \cdot a}{P_v \cdot b} \right]^{-\frac{1}{1-\rho}} \quad (16)$$

and since $\sigma = \frac{\partial \ln(V/E)}{\partial \ln(P_e/P_v)}$, we get $\sigma = 1/(1 - \rho)$.

Other production functions:

Markal-Macro assumes a three factor function to describe the output Y , of the economy as function of the primary inputs capital K , labor L , and energy services, D_m 's: the function takes the form;

$$Y_t = [a * K_t^{\rho * \alpha} * L_t^{\rho * (1-\alpha)} + \sum_m b_{mt} * D_{mt}^{\rho}]^{1/\rho} \quad (17)$$

The dual equation of this function relates the price of output P_0 , to the prices of capital P_K , labor P_L , and the prices of energy services P_m :

$$P_y = [a^{\sigma} * (P_K^{\alpha} * P_L^{(1-\alpha)})^{1-\sigma} + \sum_m (P_m/b_m)^{1-\sigma}]^{1/(1-\sigma)} \quad (18)$$

The production function finally selected in Markal-Macro assumes a factor-augmenting coefficient ddf that represents price independent technological progress like efficiency improvement.

$$Y = [a * K^{\rho * \alpha} * L^{\rho * (1-\alpha)} + \sum_m b_m * (exp^{ddf_m * \Delta t} * D_m)^{\rho}]^{1/\rho} \quad (19)$$

The dual of this equation can be estimated applying the Lagrange function, and the implicit demand function becomes:

$$D_{m,t} = exp^{-ddf_m * \Delta t * (1-\sigma)} * Y_t * (P_{m,t}/b_m)^{-\sigma} \quad (20)$$

2.2.1 Benchmarking the production function

The scaling factors a and b_m that appear in the production function (excluding the ddf factors) need to be specified for the starting year.

$$Y_t = [a * K_t^{\rho\alpha} * L_t^{\rho(1-\alpha)} + \sum_m b_m * D_{mt}^\rho]^{1/\rho} \quad (21)$$

Assuming that the parameters α , the capital's value share to the economic output and ρ (related to the elasticity of substitution), are known, we proceed as follows:

- The demand constants b_m are estimated applying the first order maximization condition for profit, where the price for energy services equals the marginal cost of energy services (change in the output per unit change of demand):

$$P_m = \partial Y / \partial D_m = b_m * (Y / D_m)^{1-\rho}$$

- Then, if each b_m is known, the coefficient a can be defined applying the production function for the first year where the labor index equals one:

$$Y^\rho = a K^{\rho\alpha} + \sum_m b_m D_m^\rho$$

Since the marginal price for energy services P_m is not a known statistical information, we have first to solve the MARKAL model in order to get the shadow prices of energy services. These shadow prices are the reference prices for the starting year that calibrate the model.

2.2.2 How MARKAL-MACRO works

The basic model advantage is that it solves for the partial and "general" equilibrium directly without the need to iterate on marginal prices. The model defines the price for energy services based on the implied demand function of MACRO and the supply functions of MARKAL.

$$D_{m,t} = \exp^{-ddf_m * \Delta t * (1-\sigma)} * Y_t * (P_{m,t} / b_m)^{-\sigma} \quad (22)$$

Simultaneously, the **production function**,

$$Y = [a * K^{\rho\alpha} * L^{\rho(1-\alpha)} + \sum_m b_m * (\exp^{ddf_m * \Delta t} * D_m)^\rho]^{1/\rho} \quad (23)$$

the basic USE identity, $Y = C + I + EC$ and the capital formation function

$K_t = (1 - \delta) * K_{t-1} + I_t$ obtain the feed-back between the energy system and the rest of the economy, using capital and labor to substitute for energy. Labor is exogenous, the energy cost EC is estimated in Markal while by maximizing of utility we specify the optimal share of output between consumption and investments.

2.3 Some final remarks

Markal includes, on the top to the energy production sector, all end-use technologies and conservation options and allows to control carbon dioxide in the end-use markets to an extent not possible in computable general equilibrium models.

This explicit description of the end-use technologies allows to model price effects on demand which go beyond the effects of long term price elasticity and analyze "better" the CO_2 control cost, i.e., to introduce back-stop technologies in the end-user's markets.⁵

Markal-Macro is a modeling invention. The reason for that claim is that Markal stand-alone is a source of significant information used to calibrate MM. The shadow prices of Markal define the reference prices for energy services and thus help to calibrate the model (specifications of a and b ,) for the starting year. Also some other parameters are defined using Markal. These are the most important parameters of the model, e.g., the elasticity of substitution $ESUB = \sigma$, which specifies substitution between the pair (K, L) and the energy services, and the demand decoupling factors DDF. This chapter explains how these parameters can be estimated.

2.3.1 Elasticity of substitution

The difficulty in estimating the parameter $ESUB$ is due to the fact that neither the energy service nor its price is a statistical information. When the energy services contribute to a small fraction of gross output, the elasticity of substitution (σ), is equal to the own-price elasticity of energy services (and not to the price elasticity of final demand). The demand for energy services (in relative terms) is given by the equation: ⁶

$$E = Y \cdot P_m^{-\sigma} \quad (24)$$

W. Hogan and A. Manne have shown that in the production function of ETA-MACRO the fuel price elasticity is given by $\epsilon_F = -\sigma/(1-s)$ where σ is the CES elasticity and s the value share of energy to the economy. A similar relation is valid also for the MM production function, where $\epsilon_E = -ESUB/(1-scs)$ refers to the price elasticity of energy services and scs to the value share of energy services to the overall output Y . The relation can be derived as follows:

Assume that the demand for energy services, in relative terms, is given as above then applying the logarithm and based on the definition of price elasticity for energy services we have:

$$\epsilon_E = \frac{\partial \ln E}{\partial \ln P_e} = -\sigma + \frac{\partial \ln Y}{\partial \ln P_e} \quad (25)$$

Thus, we see that if the economic output Y , was independent of the price for energy services then, the elasticity of substitution will be equal to the price elasticity of energy services. This

⁵"Better" means that we can describe technical conservation options which reduce demand to levels beyond the long term price elasticity. A price elasticity $\sigma = 0.4$, for example, will reduce demand by 43% if prices quadruples. At that price range it is quite probable that good insulated houses (like zero energy houses) become economic and thus a demand reduction of 80% could be obtained. Similarly, an electric car produces zero CO_2 emissions, if non-fossil electricity is used, at cost per kilometer which are probably twice or three times as high as for gasoline cars. A model based upon the elasticity of substitution requires very high taxes to produce the same reduction in CO_2 emissions. In ETA-MACRO, backstop technologies are introduced to capture the possibility to supply "unlimited energy" at high but bounded cost and thus to "backstop" prices of energy supplies. The same approach becomes possible in MARKAL for defining "backstop technologies" to the carbon tax in the end-use markets. Either capital and labor substitution for energy or the "backstop" technologies will bound the tax in a way that reflects reality better.

⁶The form of the equation is quite similar to the final energy demand equation that assumes a unitary income elasticity and a price elasticity σ .

is approximately the case when energy contributes to a small fraction of gross output. From the definition of price elasticity we have:

$$\epsilon_F = \frac{\partial \ln F}{\partial \ln P_f} = \frac{P_f}{F} \cdot \frac{\partial F}{\partial P_f} \quad \text{while} \quad \frac{\partial \ln Y}{\partial \ln P_e} = \frac{P_e}{Y} \cdot \frac{\partial Y}{\partial P_e} = \frac{P_e}{Y} \cdot \frac{\partial Y}{\partial E} \cdot \frac{\partial E}{\partial P_e} = \frac{P_e}{Y} \cdot P_e \frac{\partial E}{\partial P_e}$$

since $s_{cs} = \frac{P_e E}{Y}$, substituting we get the relation:

$$\epsilon_E = -\frac{\sigma}{1 - s_{cs}} \quad (26)$$

The equation above is not quite helpful because it correlates two unknown elasticities to each other. In order to derive a relation between the fuel price elasticity and the elasticity for energy services we have to elaborate further on the function defining energy services. We can assume that the energy services are defined by a homogeneous function of degree one (like the production function) with final energy demand F and capital Z being the main inputs, e.g., $E = g(F, Z)$ [Dantzing, 1981]. In such a case the function g , can be inverted for F to define the demand function $F = h(E, W)$, if $W = Z/F$.

The relation $F = h(E, W)$, allows to differentiate and define the partial derivative of final energy use in respect to fuel price, based on the definition of elasticity:

$$\epsilon_F = \frac{\partial \ln F}{\partial \ln P_f} = \frac{\partial F}{\partial P_f} \cdot \frac{P_f}{F} = P_f/F \cdot \left[\frac{\partial h}{\partial W} \cdot \frac{\partial W}{\partial P_f} \Big|_{E=\text{constant}} + \frac{\partial h}{\partial E} \frac{\partial E}{\partial P_f} \Big|_{W=\text{constant}} \right] \quad \text{or} \quad (27)$$

$$\epsilon_F = \frac{P_f}{F} \frac{\partial h}{\partial P_f} \Big|_{E=\text{constant}} + (P_f/E \cdot \frac{\partial E}{\partial P_f}) \cdot (E/F \cdot \frac{\partial h}{\partial E}) \Big|_{W=\text{constant}} \quad (28)$$

The first component is the technological elasticity of substitution to be estimated using Markal at constant demand for energy services. On the other hand, the second component is "behavioral driven" and refers to substitution effects due to price changes within the same technological structure. Since the demand function $E = g(F, Z)$ is homogeneous of degree 1, and the ratio $W = \frac{Z}{F} = \text{constant}$, we have $\partial F/\partial E = \partial h/\partial E = F/E$ and defining: $\epsilon_{EF} = (P_f/E \cdot \frac{\partial E}{\partial P_f})$ we get:

$$\epsilon_F = \epsilon_{Mr} + \epsilon_{EF} \quad (29)$$

Now, we can define the relation between ϵ_{EF} and the fuel price elasticity based on:

$$\epsilon_E = \frac{\partial \ln E}{\partial \ln P_E} = \frac{P_E}{E} \cdot \frac{\partial E}{\partial P_E} = \left(\frac{\partial E}{\partial P_F} \frac{P_F}{E} \right) \cdot \left(\frac{\partial P_F}{\partial P_E} \frac{P_E}{P_F} \right) = \epsilon_{EF} \cdot \left(\frac{\partial P_F}{\partial P_E} \frac{P_E}{P_F} \right) \quad (30)$$

Using the implicit price of energy services, $P_e = \frac{P_f F + P_z Z}{E}$ (or $\frac{\partial P_e}{\partial P_E} = \frac{E}{F}$)

and the definition of the fuel share α , we have:

$$\epsilon_E = \epsilon_{FE} \cdot \frac{E \cdot P_e}{F \cdot P_F} = \epsilon_{FE}/\alpha \quad (31)$$

Substituting for ϵ_{FE} we get:

$$\epsilon_F = \epsilon_{Mr} + \epsilon_E \cdot \alpha \quad (32)$$

Finally, the elasticity of substitution is:

$$\sigma = -\frac{(1 - s_{cs})}{\alpha} \cdot (\epsilon_F - \epsilon_{Mr}) \quad (33)$$

This relation allows to assess a feasibility range for the elasticity of substitution. The fuel price elasticity can be estimated by econometric analysis of the energy markets. Also, the technological elasticity and the other constants are estimated within the modeling framework used. If the model uses data that imply a high technological flexibility to substitute for energy services then, ϵ_{Mr} gets a high value. But, at high technological substitution and constant fuel elasticity, the elasticity of substitution becomes smaller. Thus in that case the model becomes less sensitive to price changes and lowers the chance to double-count energy savings.

Estimating ESUB

Based on the relations discussed above an appropriate range of ESUB can be defined. The exact value of ESUB is not easily estimated since the assumptions concerning the homogeneous function of energy services are not always fulfilled. Markal assumes initial stocks of capacity and bounds that distort the homogeneous function. Also, the relations defined refer to a static representation of the markets while in our modeling approach we use a dynamic multisectoral market representation. Examining the Markal results in the reference cases and at different prices we specify the technological elasticity of substitution to be between 0.1 to 0.2. The low estimate refers to cumulative final demand change while the high value refers to the demand in the year 2030. (Markal is a multiperiod and multisectoral model and that makes it difficult to estimate one elasticity based on the aggregate definition $\epsilon_{Mr} = \frac{\partial \ln F}{\partial \ln P_f}$).

The procedure to estimate an aggregate energy price elasticity is based on econometric analysis and time series that define prices, final energy use per fuel and the GDP of Switzerland. In order to define the price and the income elasticities we assumed a demand relation similar to the one used in Markal-Macro,

$$F_t = Y_t^\beta * P_f^{\epsilon_f} \quad (34)$$

F_t is the final demand and P_f the aggregate energy price index. Ordinary least square analysis has been performed using constructed time series on average energy prices, final energy demands and the GDP. This analysis gives a very low price elasticity $\epsilon_f = -0.1$ and an income elasticity $\beta = 0.75$. On the other hand, the short and long term elasticities for Switzerland are much higher. Finally, values of $\epsilon_f = -0.2$ to -0.4 have been adopted for Switzerland.

Assuming again that the fuel cost is 50 % of the end-use device costs, the elasticity of energy services gets similar values to the price elasticities and varies between -0.2 to -0.4. If again, the value share of energy services to the total output is 0.15 then, the elasticity of substitution will be in the range of 0.17 to 0.34. The value adopted for Switzerland was 0.2 for being in the conservative side and not underestimating the carbon tax.

2.3.2 The demand decoupling factor, DDF

The DDF factor simulates technological progress in the energy sector but it can have different interpretations. The most common one is that represents efficiency improvement independent of price changes. Another interpretation is that adjusts for the non-unitary income elasticity of demand. Finally, ddf can be related to the structural changes in the economy and the life style changes. It follows an innovative interpretation of the ddf parameters.

In MM the demand for energy services becomes an endogenous model variable. Generally, it is not justified to generate disaggregated demand projections based on aggregate levels of economic activity and an average elasticity of substitution. One has to differentiate between sectors of

high or low demand growth that differ to the average economic growth. For this reason MM can be calibrated to the time dependent projections of more sophisticated simulation models. This calibration is obtained by defining time and sector dependent demand decoupling factors. In this way, different scenarios can be simulated by defining different parameters per scenario. Energy demand becomes a real model variable only under the CO_2 constraint. The procedure for the calibration is as follows:

In order to specify variable ddf factors per energy service and time step that mimic the results of other demand simulation models, a production function is used where technological progress is explicitly assumed. The function takes the form,

$$Y = [a \cdot K^{\rho \cdot \alpha} \cdot L^{\rho(1-\alpha)} + \sum_i b_i \cdot (\exp^{ddf_i \cdot \Delta t} \cdot D_i)^{\rho}]^{1/\rho} \quad (35)$$

and links the primary input requirements of the economy, capital K , and labor L , to the energy services, D_i . The ddf 's augment the production factor energy such that less energy is used for the same output. The dual equation is derived from $P_i = \partial Y / \partial D_i$ and relates the price of energy services to their demand:

$$D_{i,t} = \exp^{-ddf_i \cdot \Delta t(1-\sigma)} \cdot Y_t \cdot (P_{i,t}/b_i)^{-\sigma} \quad (36)$$

The relation is reformulated introducing a time period index k .

$$D_{i,t} = \exp\left[\sum_{k=1}^{k=t} -ddf_{i,k} \cdot \delta t \cdot (1-\sigma)\right] \cdot Y_t \cdot (P_{i,t}/b_i)^{-\sigma} \quad (37)$$

where δt is the time step per period. If all the parameters and variables of the equation above are known, then the $ddf_{i,k}$ can be specified applying the relation to each time period. Now, using the MARKAL estimates of shadow prices per demand $P_{i,t}$, the assumed economic growth and the demand projections of the simulation models, $D_{i,t}$ (e.g., the exogenous demand constraints of MARKAL), we can define $ddf_{i,k}$ as follows:

$$\begin{aligned} ddf_i &= 0.0 \quad \text{for the first period} \\ \text{and for } k &= 2, 3, \dots, t \\ F_{i,k} &= D_{i,k} / (Y_k \cdot P_{i,k}^{-\sigma}) \\ ddf_{i,k} &= \ln(F_{i,k}/F_{i,k-1}) \cdot (\rho - 1) / (\delta t \cdot \rho) \end{aligned} \quad (38)$$

$$(39)$$

The procedure has been used for Switzerland and other countries. The user must start with Markal and estimate the shadow prices for energy services and iterate with MM for the correct estimate of the economic output.

In conclusion: One of the main problems in using MM is to avoid double-counting of energy conservation. For that purpose, the model user should start with the proper estimate of the elasticity of substitution. The adopted value for ESUB must be consistent with the database and the known price elasticity of energy demand. Then, if more sophisticated demand projections are available for the reference case, time dependent ddf factors can be introduced that simulate these projections. This preliminary analysis is a prerequisite in order to have consistent estimates of marginal CO_2 control cost.

3 Economic Implications of Environmental Policy

3.1 Scope of the study

The greenhouse effect is one of the most critical issues in environmental policy. The UN framework Convention on Climate Change, article 2, states that: **The ultimate objective of the Convention ... is to achieve, ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.**

At present, the global carbon dioxide emissions increase at a rate of approximately 1% per annum. Other greenhouse gases (GHGs) show also similar trends while their atmospheric concentration increases. This produces a global warming since more heat is trapped by the earth's atmosphere. IPCC models [IPCC-90] indicate that even a stabilization of **emissions** to present levels produces a linear increase in CO_2 concentrations. In other words, a stabilization of CO_2 **concentrations** is only possible if the GHG emission rate is reduced. Global warming will be stabilized between 1.5°C to 4°C higher than present temperatures as long as the global GHG emissions are reduced at a rate of approximately 1% per year. This decrease of emissions will stabilize GHG concentrations to levels of 50% more than the pre-industrial concentrations. This was also the recommendation of the Toronto Conference in 1988 [UN, 1988]. Thus, in order to fulfill the ultimate objective of the Convention on Climate Change and to "prevent dangerous anthropogenic interference with the climate system" we have to reduce CO_2 emissions by 50% in the next century. Most of the natural scientists and the environmentalists see no reason to argue about these goals. On the other hand, most of the economists argue about timing, the measures and the level of carbon tax necessary to address the problem. They claim that the world economy itself is a very sensitive and complex system and that unwise and unrealistic policy could damage the economy in an irreversible way. Also, the optimal policy, i.e. a policy that takes into account the control costs and the benefits to avoid damages is not justifying high levels of carbon taxes. This is an ongoing debate.

The interpretation of this Convention in terms of goals, appropriate measures and timing needs further elaboration. On the other hand, one can assume that a uniform and unilateral CO_2 emission reduction by 50% for all countries is a first option to start with analysis and define the economic implications of CO_2 control. The next step is to search for more efficient policies and differentiate among countries with different control costs and energy systems.

The **scope of the study** is to examine the economic implication of fulfilling the UN framework Convention on Climate Change by assuming different reduction levels of CO_2 emissions in Switzerland, relative to the emissions of the year 1990. The study continues with the examination of more efficient means of environmental policy like compensation payments for investments that mitigate global warming and the international trade of CO_2 emission rights, and concludes with a stochastic analysis to define "minimum regret" policy for Switzerland.

The improvement of the ambient air quality in Switzerland can be obtained by reducing the annual emissions of SO_2 and NO_x , as proposed by the "Clean Air Concept" of the Swiss administration [LRK-1988]. This is introduced in all scenarios analyzed and the study identifies the synergies of a combined policy against the global warming and the improvement of the local ambient air

quality.

3.2 Main Assumptions

The study on the CO_2 control cost is based on the scenario approach. A scenario is a set of consistent assumptions describing the underlying social, political and economic developments in the country as well as the necessary policy framework to implement the assumed development. Different scenarios are described using the model Markal-Macro.⁷ The value of ESUB for Switzerland is assumed to be 0.2. This is justified due to the low level of substitution for energy that has taken place in the country and the low price elasticity of demand.

- Socioeconomic parameters.

The assessment of the socioeconomic development i.e., population, Gross Domestic Product (GDP) growth, industrial production, building stock development and car ownership, as specified by the St. Gallen Centre for Future Research, has been used in this study [SGZZ, 1990]. The assumed population growth (0,3 %/a) combined with moderate productivity growth, allows an economic development of 1.55 %/a, up to the year 2000 which is then reduced to 1.28%. Therefore, the potential GDP increase is 70%. These assumptions refer to an economic environment under a nuclear moratorium.

- Energy demand.

The socioeconomic parameters together with an assessment of the evolution of the specific energy consumption have been used by a sectorial demand simulation model SMEDE [S. Kypreos, 1990] to define the energy demand constraints for Markal. This data correspond to the expectations on economic growth and structural changes in Switzerland. Finally, the shadow prices for energy services of Markal are used to define the so-called DDF factors for Markal-Macro and to calibrate the model such that the same disaggregated demand of energy services is estimated in both models. Energy demand becomes a real model variable under the CO_2 constraint and allows to study the economic implications of CO_2 control policy. Finally, the explicit assumptions on technological change made in the demand simulation model SMEDE and in the data base of Markal result to a stabilization of final energy demand for the price development of the reference case.

- The end-user's price for oil and gas are exogenous and it is assumed to double in the next 15 years and from then on to remain constant up to the year 2030.

- It is important to distinguish between the marginal productivity of capital c_r and the rate of time preference r used in discounting of the utility across different generations. The relation between these two rates for the logarithmic form of utility function used is: $c_r = g + r$ where g is the growth rate of the economy.

The study assumes a real capital productivity $c_r = 5\%$, while g is an endogenous model variable that depends on potential growth and on the cost of the energy system including environmental control. The average economic growth assumed under a nuclear moratorium is given above and in Table 1 which is a summary of the main assumptions.

⁷ Most of the data, price assumptions and demand projections are based on the work of EGES [1998]. Work is progress for updating the database of the model.

Table 1: Main scenario assumptions

indicator	units	1990	2030
population	million	6.72	7.3
GDP	relative to 1990	1.	1.7
GDP	Billion SFr 90	314.	534.
industry & construction	GDP fraction	0.35	0.35
energy/industrial GDP	relative to 90	1.	0.7
commercial sector	GDP fraction	0.61	0.63
		1990	2025
freight	10^6 tkm	18.	20.
car ownership	cars/1000 cap	447	535
share of car transport	percent	.77	.76
car-km	10^6 km	45.	50.
energy/car-km	relative to 90	1.	.7
heated surface	m^2/cap	63.3	82.
useful energy/ surface	relative to 90	1.	0.79
oil price (dollars/barrel)		18	36

3.3 Scenarios and Emissions

All the assumptions discussed before, define the expected energy demand for the present energy and environmental policy and the expected price development. This demand projection is associated with a nuclear "Moratorium" (MO) imposed by public vote in 1990. It is assumed that the total installed nuclear capacity will remain in the level of 3. GWe to 3.25 GWe independently of the aging of nuclear reactors. This becomes feasible by extending the life of existing plants. Another scenario called "Nuclear Available" (NA), is introduced for testing the GDP differential and the carbon-tax differentials due to the nuclear availability. It has been assumed that new nuclear power stations will be made operational after the year 2010 while their capacity is unconstrained. Similarly, the oil and gas imports are unconstrained for all scenarios analyzed in the study.

Sustainability constraints on environmental quality are imposed to avoid emissions causing local, regional and global pollution problems. Imposing appropriate bounds on annual emission levels we are able to satisfy policy goals on environmental quality as adopted by the Swiss "clean air act" and to contribute to the global climatic sustainability as proposed by the "Intergovernmental Panel on Climate Change".

In the reference case the emissions of CO_2 are not constrained at all, while in all cases the emissions of SO_2 and NO_x where constrained to levels which represent the "clean air concept" proposed by the Swiss Government.

Different scenarios on the **CO_2 constraint** are defined based on gradually increased limits on CO_2 emissions. The MO and NA cases are estimated first without imposing a constraint on CO_2 . Then, different cases are analyzed with the optimization model at different levels of CO_2 control, starting with a stabilization of emissions and ending with a reduction rate of 50% in the year 2030. The reduction rates refer to the emissions relative to the year 1990.

It is of importance to notice that the SO_2 constraint becomes nonbinding and the marginal cost related to the NO_x constraint is strongly reduced by imposing severe CO_2 constraints. Thus, we can conclude that the required structural changes of the Swiss energy system necessary to fulfill the Climate Convention improve the local and regional ambient air quality at no extra costs.

4 Main Results

This chapter presents a summary of the Markal-Macro results for the "Moratorium" and the "Nuclear Available" cases. This summary gives the primary and final energy, the electricity generation, the marginal control costs and the economic implications in terms of GDP losses. Finally, the contribution to CO_2 reduction by technology and due changes in energy prices and the economic output is presented and discussed.

4.1 Primary Energy

Primary energy consumption increases between 34% (CO_2 -unconstrained) and 16.4% (CO_2 constrained case), in the NA case. In the MO unconstrained case, the primary energy increases by 18% and remains constant in the 50% CO_2 reduction case. Total primary energy requirements (TPER) are given in Table 2 and for the different scenarios.

The level of primary energy use for the unconstrained reference development is in principle exogenous to MM. This depends on the level of technical innovation assumed in the demand simulation model and the doubling of consumer's prices in the final energy markets. On the other hand, the difference in primary energy use between the NA and the MO cases is endogenous and depends on the difference in their marginal costs of energy services. The high production cost of solar electricity in relation to nuclear electricity augments the marginal costs of demands and makes explicit conservation measures attractive. The high marginal cost of demands in the MO case reduces the equilibrium level of demand.

The marginal costs of energy demand are even higher when a carbon constraint is introduced. This is due to substitution of fossil fuels by non-fossil alternatives. The high marginal costs reduce demand for energy services (ESUB=0.2) while the explicit conservation options in the end-use markets become more competitive.

Table 2: Primary energy in 2030 (PJ/yr)

case / CO_2 reduction	base	0%	20%	30%	40%	50%
Nuclear available	1348	1353	1326	1268	1224	1175
Moratorium	1192	1165	1126	1116	1053	1000

4.2 Shares of Fossil, Nuclear and Renewable Energy

The imposed CO_2 emission constraint results into significant changes in the structure of energy supplies: inter-fossil fuel switching (which has taken place in the base case and between the years 1990 and 2030) is important only at moderate levels of CO_2 reduction. Fossil fuel use is substituted by mainly nuclear energy and renewables, in the NA case and at high levels of CO_2 reduction. Two effects take place in the NA constrained case: the carbon tax increases the fossil fuel cost of end-use technologies and thus electricity substitutes for fossil fuels, while the low generation cost for electricity makes conservation options in the electricity markets less competitive. The net effect is a higher use of electricity to substitute for fossil fuels and a higher production of electricity from non-fossil fuels.

The nuclear energy gains 26 percentage points (pp) relative to 1990, versus 2 pp losses in the contribution of renewables and 24 pp loss by fossil fuels. The inter-fossil fuel shares for the year 2030

and at -30% CO_2 reduction are quite the same in both cases. Table 3 gives the shares of fossil fuels, renewables and nuclear energy as well as the inter-fossil fuel shares.

Table 3: Shares of Primary Energy (2030)

Fuel	base MO	-20% MO	-30% MO	base NA	-20% NA	-30% NA
nuclear	.242	.256	.258	.386	.452	.478
renewables	.171	.273	.326	.147	.152	.162
fossil	.587	.472	.416	.485	.396	.360

fossil fuel distribution (2030)

oil	.417	.52	.524	.459	.543	.538
gas	.427	.462	.456	.421	.427	.442
coal	.156	.018	.02	.120	.030	.020

Fig. 2 illustrates the primary energy use for the unconstrained and the 30% CO_2 reduction cases. Segments in the bars (bottom to top) correspond to coal, wood, oil, gas, nuclear energy and renewables.

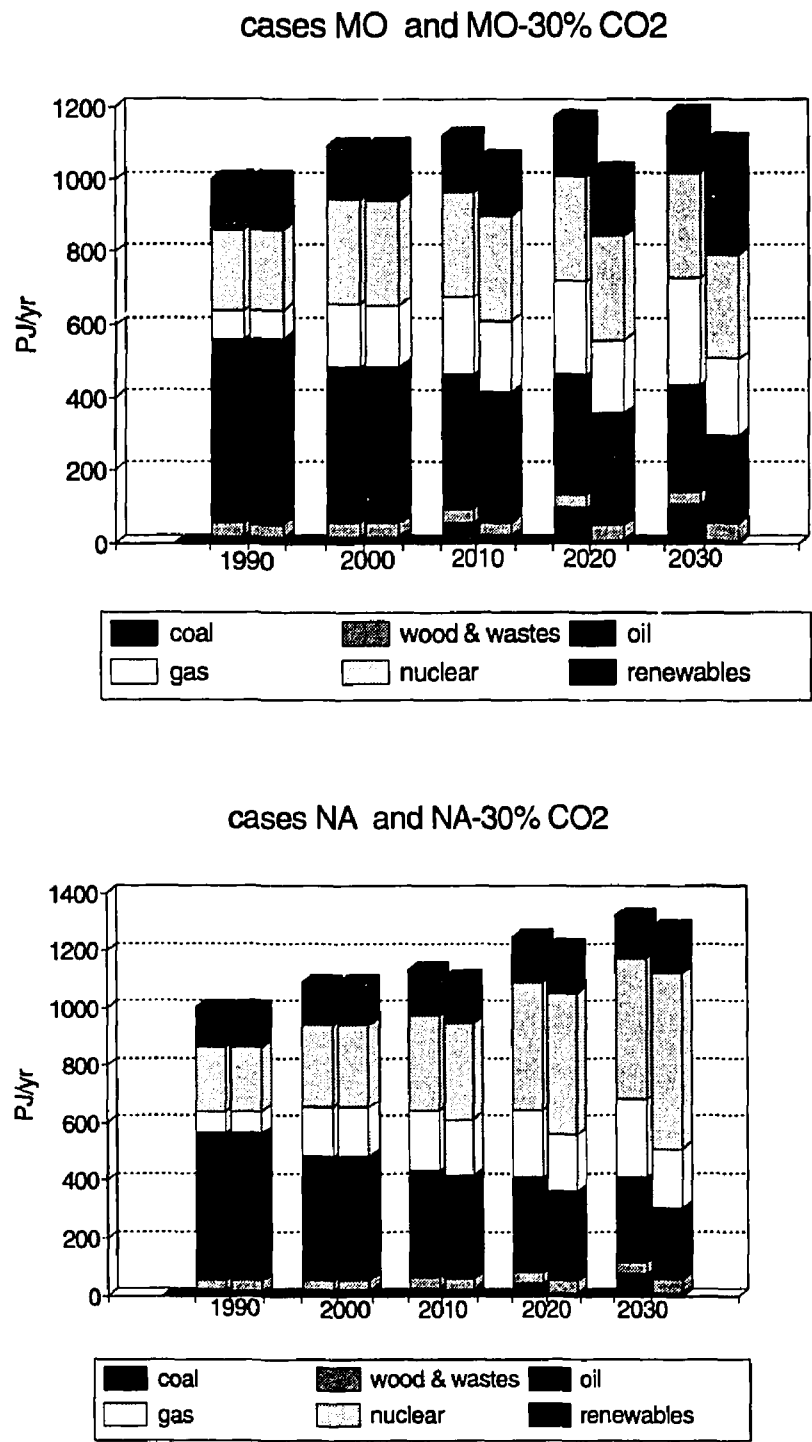


Fig. 2: Primary energy use per scenario

4.3 Final Energy

The final energy consumption increases less than the primary energy. This is due to the use of fossil fuel equivalent to account for nuclear and solar electricity. The nuclear availability case assumes a higher demand level than in the Moratorium case. The difference is due to the fact that conservation measures become less attractive (competitive) in the nuclear availability cases. In the NA case and when a 30% reduction of CO_2 emissions is imposed, demand is stabilized to the levels of 1990, while in the MO case final energy decreases by 4%. The M-M results are similar, but lower, to the Markal stand-alone results. This is due to the fact that in M-M the increased marginal costs of energy services under the CO_2 constraint, lowers demand by an equivalent price elasticity of 0.2. Another difference in the results refers to the estimated fuel shares. Since gas is not anymore bounded, the share of liquid fuels decreases to approximately 32%. Liquid fuels are loosing 32 pp relative to the 1990's share, gas captures 15 pp and electricity 13 pp.

Table 4: Final Energy in 2030 (PJ/yr)
(779 PJ in 1990)

case	base	0%	20%	30%
Moratorium	846	826	786	746
Nuclear available	893	893	838	778

4.4 Electricity Production

In the Moratorium reference case, the new production is covered by different fossil fuels (coal for industrial cogeneration, gas and oil) and hydropower. The contribution of renewables and nuclear energy is less important. In the CO_2 reduction cases solar, hydro and wind substitute for fossil fuels with the exception of small cogeneration systems for services and residential buildings. The potential of hydro-power, solar tower (in the Apls), wind and photovoltaics is rather optimistic. Significant is also the extra contribution of nuclear energy under the conditions of nuclear moratorium.

In the nuclear available case, electricity is now generated by nuclear energy instead of solar electricity and hydro, while conservation options become less attractive (non-competitive). The nuclear installed capacity is increased to 6.9 GWe by the year 2030, from 3.1 GWe in 1990, which means almost a new nuclear reactor every six years, beginning with the year 2010. Table 5 illustrates the situation.

Table 5: Electricity production by technology in the year 2030 (PJ/yr)

technology	1990	MO base	MO -30%	NA base	NA -30%
hydro	110	132	135	120	118
nuclear	74	92	92	157	196
wind and solar	-	27	47	-	-
fossil	3	64	7	23	-
total	187	289	283	300	314

4.5 Carbon Tax and Economic Implications

This paragraph gives the marginal costs due to CO_2 control. The estimated marginal costs are proper estimates of the carbon tax required to meet the imposed constraints because the model

reflects the feed-backs of the energy system to economic growth and the price effects on demand. Table 6 gives the marginal cost, the GDP reduction per scenario and the annualized energy system cost index relative to 1990.

**Table 6: Marginal CO_2 Control Cost (SFr/ton)
Moratorium (rounded values)**

case MO	2000	2010	2020	2030
Stabilization	-	5	30	50
-20 % CO_2	-	60	175	265
-30 % CO_2	-	155	270	385
-50 % CO_2	-	250	485	1210

Nuclear Available (rounded values)

case NA	2000	2010	2020	2030
Stabilization	-	-	-	-
-20 % CO_2	-	50	120	190
-30 % CO_2	-	120	200	400
-50 % CO_2	-	220	520	1210

GDP Relative to 1990

case	2000	2010	2020	2030
MO base	1.15	1.32	1.53	1.77
MO -30% CO_2	1.15	1.31	1.50	1.74
MO -50% CO_2	1.14	1.30	1.47	1.69
NA base	1.15	1.32	1.53	1.77
NA -30%	1.15	1.31	1.51	1.75
NA -50%	1.15	1.31	1.48	1.70

Annualized Energy Cost (2030) Relative to 1990

MO base	MO -30%	MO -50%	NA base	NA -30%	NA -50%
1.58	1.47	1.44	1.58	1.48	1.47

Comparing the nuclear moratorium versus the nuclear availability cases we can summarize the conclusions as follows:

In both cases, the energy system cost is reduced when applying the CO_2 constraint. This result is the net outcome of two effects working in the opposite direction:

First, capital intensive technologies substitute for fossil fuels and increase the annualized cost. On the other hand, the reduced energy demand lowers the fuel cost. Since the price effects in the MO case are stronger, than in the NA case, energy demand and fuel cost is lower in the MO constraint cases.

The carbon constraint makes the unit cost of energy expensive, as illustrated by the level of the estimated marginal costs. The marginal cost differentials between the MO and the NA cases are only important at low reduction levels. Actually, in the NA stabilization case the CO_2 constraint is non-binding. This means that under the nuclear availability CO_2 emissions can be stabilized without imposing carbon taxes. The study though, assumes a doubling of energy prices and a high degree of technical innovation for the reference development.

Finally, the GDP reduction varies between 1.7% GDP loss in the 30% reduction case, and 4.5% GDP loss in the 50 % reduction case. Another interesting index is to define the GDP per capita for the cases with and without CO_2 control. The index is 76.1 kSfr in the unconstrained cases and it is reduced to 72.7 kSfr, at 50% emission reduction, starting from 46.7 kSfr in 1990. In other words, a 50 % reduction of CO_2 emissions is associated with annual GDP losses of 3.4 kSfr per capita. This level is probably approaching the limits on the Swiss willingness to pay for protecting the environment. More cost efficient and effective policies must be proposed than a unilateral reduction of emissions by 50%.

4.6 CO_2 Reduction by Technology and Price Effects

One of the most interesting questions of this analysis is to evaluate the contributions of different technologies or set of technologies to CO_2 control versus the price effects on demand and the reduction of economic activity.

Using an adjusted to the model definition of CO_2 emission balance introduced by Prof. Kaya, we get the components of CO_2 reduction that compare two scenarios. This is illustrated in the following figures and table 7. Notice that the term change in "efficiency" means changes in the average efficiency that transfers primary energy use to demand for energy services. The use of primary fossil equivalents to account for nuclear and solar systems asks for a careful interpretation of the term "efficiency".

Table 7: CO_2 Reduction by Technology and Price Effects in Mt/yr
Comparison between baseline emissions and -50% reduction in 2030

component	Moratorium	Nuclear available
change of economic output	1.3	1.
price changes of demand	2.3	1.75
changes in "efficiency"	1.7	0.6
share of nuclear energy	2.7	11.7
share of renewals (incl. wood)	17.5	7.2
inter-fossil fuel switch	0.7	0.0
total reduction	26.2	22.2

As seen in the subsequent figures, in the MO cases, most of the reduction is due to the contribution of renewables and mainly solar energy. In the nuclear availability case nuclear energy, followed by renewables have the highest contribution.

Inter-fossil fuel switch has a strong contribution between the starting year 1990 and the year 2030, in the reference development. It is not important at all for the constrained scenarios. The nuclear unconstrained development assumes 4 Mt less emissions by the year 2030.

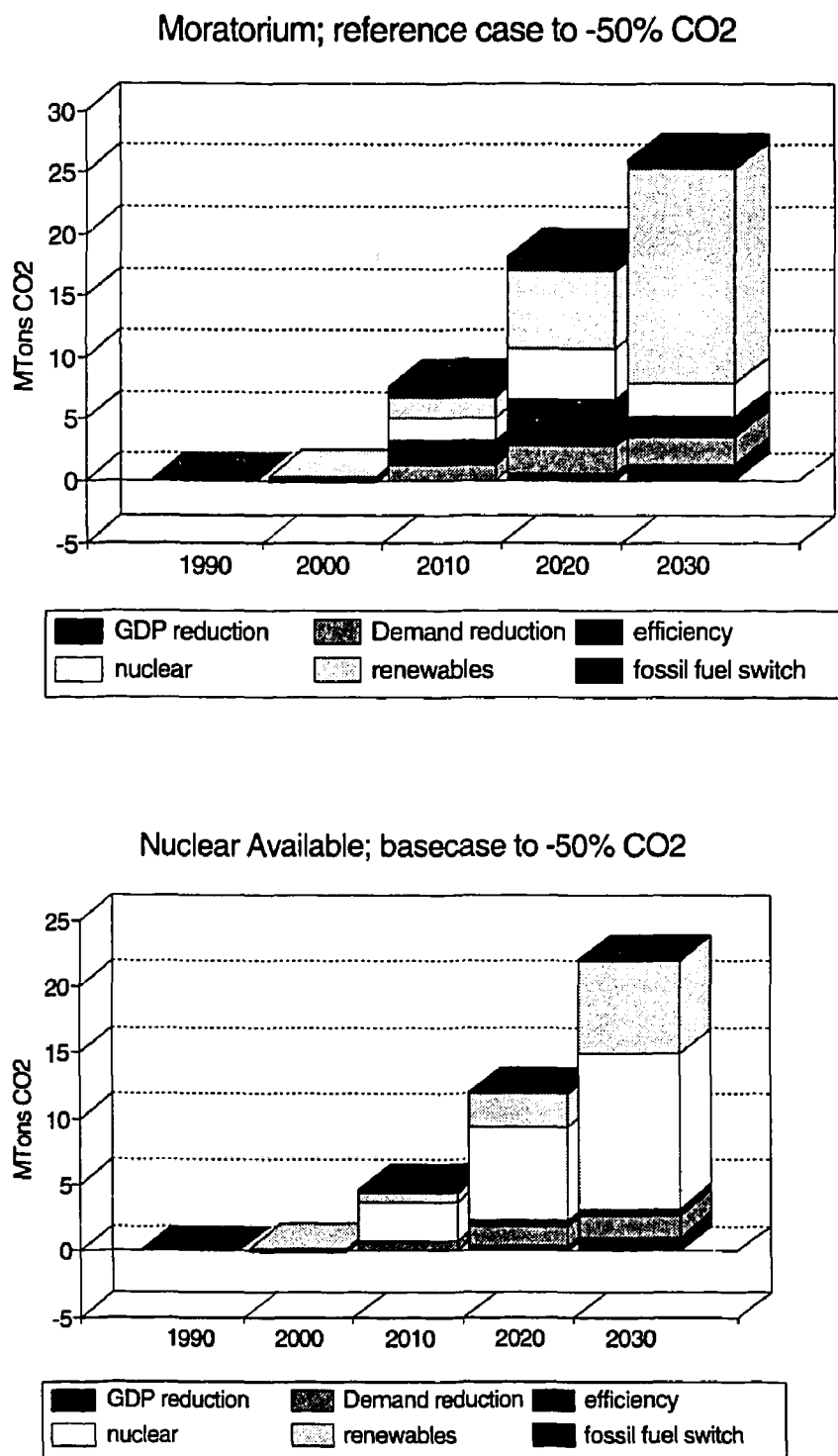


Fig. 3: Time dependence of CO₂ reduction; Cases Moratorium and NA

5 Asking for Efficient Policies

Examining the results shown before and putting them in an international perspective [T. Kram, 1993] we conclude that Switzerland has high CO_2 control costs. This is because of the high efficiency in energy use and the absence of coal as primary fuel for electricity generation. The high control costs imply high carbon taxes and low public acceptance for environmental policy. In order to study possibilities of more efficient environmental policies than a uniform percentage reduction, some other options are further quantified as:

- Trade-offs between CO_2 and other GHGs:
Here, instead of analyzing the control costs of CO_2 alone all other greenhouse gases are considered and the trade-offs are estimated.
- A tax-compensation approach:
Here, taxes are imposed on the national level while the tax revenue is used to compensate for investments on CO_2 mitigation options.
- Trade on carbon rights:
Transfer payments across nations are introduced to purchase emission rights, and to capitalize on the structural cost differences among nations and to identify cost efficient strategies in mitigating CO_2 .

The first policy increases our flexibility by mitigating all different GHGs. The last two policies are in principle methods to finance technological change in the national and international level for CO_2 mitigation while penalizing the use of fossil fuels by the introduction of a tax-rate proportional to their carbon content. Both policies can be quantified by formulating non-linear mathematical programming models where many countries or world regions are involved. These large scale models can only be solved by decomposition methods. The results presented below are multinational results of Markal used alone and not of Markal-Macro. This is due to the fact that the decomposition algorithm used to study international trade for non-linear problems is not established yet. Apart of this limitation, the conclusions discussed here are of general validity.

5.1 Trade-offs between CO_2 and other GHGs

The equivalence between the different GHGs is defined based on their global warming potential (GWP). With the flexibility to trade-off emission reduction between different GHGs, Switzerland could more effectively contribute to climate stabilization. At marginal costs of 150 SFr per ton CO_2 equivalent, Switzerland could reduce the major greenhouse gases by 30% from their 1990 level. Most of this reduction is due to CFCs and only 25% is due to CO_2 .

5.2 A Tax-Compensation Approach

Another promising efficient option is to combine a carbon tax with compensation payments to technologies that mitigate GHGs. An effort has been undertaken to reformulate the optimization model Markal for that purpose. The model selects the most appropriate technologies for receiving compensation payments, defines the amount of capital investments to be compensated and redistributes the tax revenue. These technologies are conservation options, renewable technologies and end-use devices that substitute for fossil fuels or CO_2 abatement technologies.

A budget constraint is introduced in Markal that distributes the tax revenue among the candidate technologies to receive compensation. The compensation is a fixed fraction of the initial investments to technologies that mitigate CO_2 . A variable fraction has been also proposed but the problem becomes non-linear and very difficult to solve. The most efficient compensation level of initial investments that reduces the CO_2 emissions at maximum, is a function of the imposed tax. Therefore, in order to specify the appropriate tax and the fractional reduction of initial investments, a parametric analysis is performed, as described in [S. Kypreos, 1993]. Fig. 4 compares the emission profiles with a pure tax and under a tax compensation scheme. The results refer to the Moratorium case. The "base" case refers to the results without tax. The \$ 200/ton C refers to a pure tax policy, while the last case refers to a tax-compensation policy. Some basic conclusions

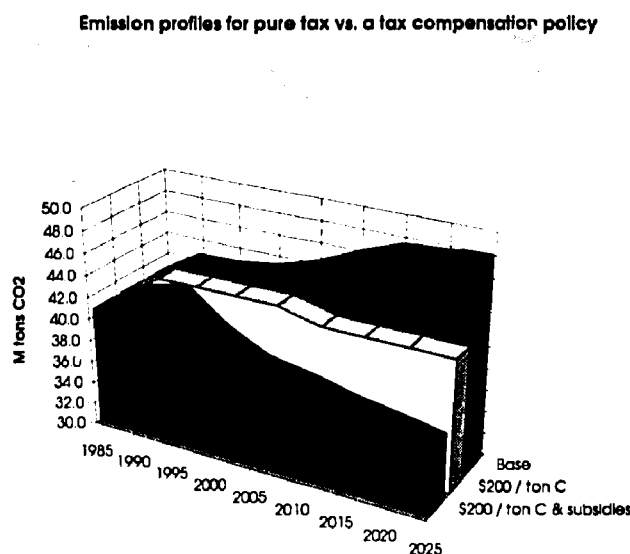


Fig. 4: Emission profiles for pure tax versus tax-compensation

can be derived out of this analysis:

The lower the imposed tax-rate the more important it is to introduce compensation payments and to enhance the efficient use of tax revenues. At \$ 200 per ton of carbon, Switzerland slightly reduces the emissions relative to the 1990's level. The introduction of a tax-compensation policy will reduce emissions by 16%. Finally, a tax rate of 300 dollars per ton of carbon (or 120 SFr per ton CO_2) combined with compensation payments is sufficient for reducing emissions by 20% below the 1990's level.

5.3 International Cooperation

The strong differences in the structure of the energy systems across the OECD countries and between OECD and third world countries enhances the possibility to gain from trading emission permits and asks for international cooperation. It would be more effective for the group of countries with high marginal control costs to purchase emission permits from the group of countries with low marginal cost, instead of investing in their own national border for mitigating CO_2 emissions. The trade of emissions will help to obtain the same absolute emission reduction on the global level, but at considerably reduced costs, since the most cost efficient measures will be selected.

Typical examples of studies that estimate the benefits of trade is the work of A. Manne and Th. Rutherford, 1993 and the OECD study that applies the GREEN [O. Martins, 1992] model. Recent work of the Energy Modelling Forum study 14, gives some more examples on the benefits of trade. But, the aggregate nature of the world regions excludes a detailed treatment of energy, environment and the economy. National models, on the other hand, are more detailed and represent the organization level for people that allows to make decisions and apply policy. Integration of national models allows to assess the benefits of trade in details but increases the size of the overall model. An example of such an analysis is presented by O. Bahn. He uses decomposition methods for large scale linear models of different OECD countries. In this example Switzerland, the Netherlands and Belgium are cooperating in order to reduce their present emissions by 20% in the year 2030. The method used, the results obtained and the main conclusions are explained in [O. Bahn, 1993] and they are illustrated in Fig. 5

This figure shows that Switzerland will gain the most when participating in such a cooperation. The optimal strategy reduces the tax level below 100 dollars per ton-C (40 SFr per ton CO_2) without introducing compensation schemes.

Further reduction of tax rates are expected by applying a policy of emission trade in the international level combined with tax-compensation payments on the national level. The quantification of such policies needs the use of non-linear programming. Also, the analysis of macroeconomic implications and the feedbacks between environmental policy and economic growth need the use of non-linear approaches. It will be of interest for the international community to try to investigate such options using a set of simplified general equilibrium submodels for the OECD and the main third world countries with an explicit treatment of the energy sector, and define the benefits of trade.

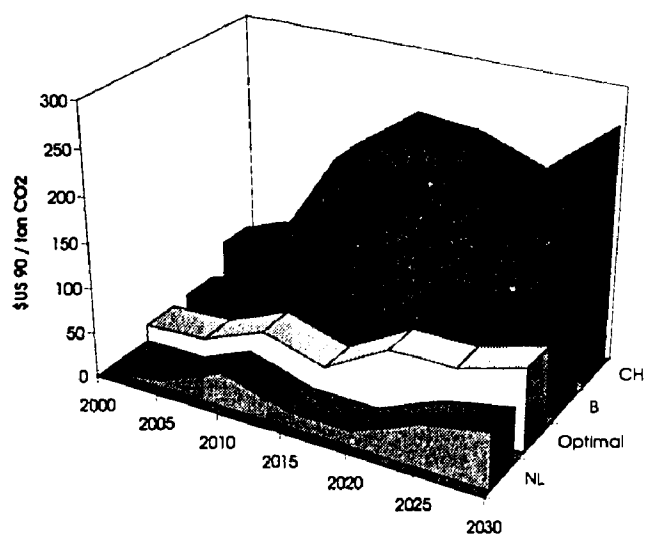
Undiscounted marginal costs of CO₂ reduction

Fig. 5: The benefits of CO₂ trade; Marginal CO₂ control cost profiles for countries under cooperation versus unilateral control strategies. Switzerland, the country with the highest marginal cost assumes the highest benefit.

6 Stochastic Analysis

Uncertainty is the essence of the climate change issue. The main source of uncertainty is associated with the physics of the climate change, and consequently with the policy implications concerning the level and the rate of CO_2 emission reduction or the acceptable equilibrium CO_2 concentration in the atmosphere. Such a situation makes it difficult to conclude on policy but, uncertainty should not be a synonym of paralysis.⁸

In the previous chapter, we have been assessing uncertain or conflicting issues by defining different scenarios. Each scenario corresponds to a given exogenous set of assumptions concerning the level of introduction of the uncertain parameters. For example, peoples disagree concerning the importance and the safety of nuclear energy. Thus, a nuclear available scenario and a nuclear moratorium are analyzed separately in order to define the implications of these alternative choices. Each scenario or **state of the world** $s=1,...,S$, corresponds to a given selection (assumption) concerning the value of the exogenous variables for which uncertainty applies. For instance, CO_2 emissions may not be restricted in the forthcoming decades, or may have to be stabilized or even reduced significantly, say by 2030. Thus, a business-as-usual (BAU) scenario, a stabilization scenario and a reduction scenario can be defined to analyze the implications of these alternative environmental policies. These $S=3$ scenarios, that have to be analyzed separately, can be described as shown in Fig. 6. (when the time horizon is 1990-2030).

Notice that for each scenario $s=1,...,S$, all uncertainties must be resolved before taking decision. Such a method requires to guess (learn) the state of the world before taking action (**learn-then-act** approach). Moreover, it does not deliver a single set of recommendations (results), but as much as the number of scenarios studied. Results are then presented for different assumptions on economic growth and fuel prices and for different environmental policies.

In the scenario approach, the best we can do is to identify and select robust technologies (i.e., technologies that contribute to all or most of the scenarios analyzed) as key technologies for making investments in the energy sector or for R&D support.

6.1 Mathematics and Terminology

Instead of the deterministic scenario analysis a stochastic approach can be used where the **expected cost or the expected utility** are taken into account as criterion of decision making. Assuming that the unknown and uncertain "nature" will be revealed at a time point in the future we can define our policy now by making decisions that take future uncertainty in to account. This improves our flexibility and defines a more balanced approach a kind of insurance against risk, i.e., a **hedging approach**. Further more, **risk aversion** can be taken also into consideration when

⁸There are other uncertainties related to the policy analysis for energy and the environment, like:

- The population development and the economic growth;
- The contribution of nuclear energy since the public opinion is divided;
- Security of energy supply, fuel prices and demand;
- Conservation options and the rate of technical innovation;
- Economics of scale and the learning curve for new technologies.

A comprehensive method that takes all these uncertainties into account and concludes on policy decisions is very helpful, to my opinion, in establishing a political compromise based on scientific knowledge.

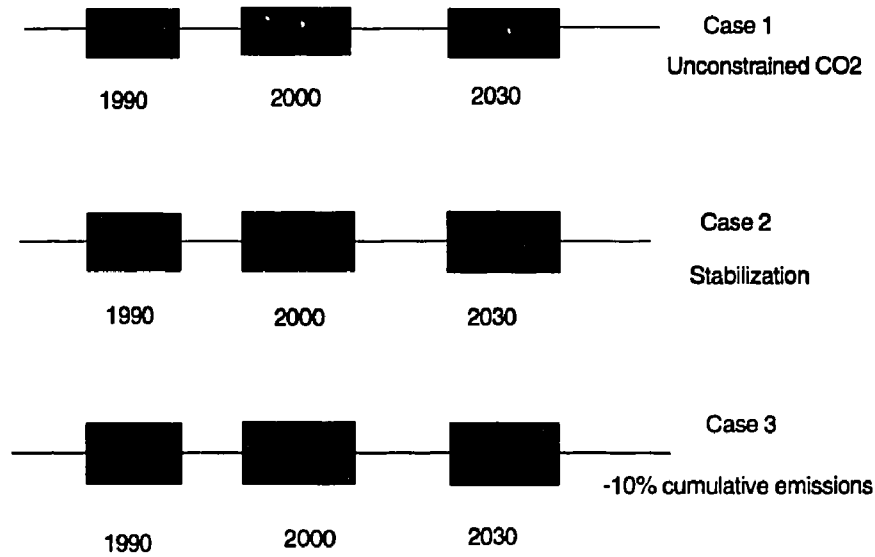


Figure 6: Three cases for the scenario-by-scenario analysis are defined to study different CO_2 reduction policies

making investments in the energy sector.

Suppose that we can define again $S=3$ alternative CO_2 reduction policies (no reduction, stabilization and reduction to be reached by 2030) to define three states of the world (scenarios). And suppose that we can associate to each scenario $s = 1, \dots, S$, a probability P_s . We assume furthermore that all uncertainty related to the climate change issue will be revealed by the year 2010, so as to know by that date which environmental policy to follow. The decision variables describing these policies can be grouped into two categories: x_1 , the decisions to be determined prior to the year 2010 (that is before the resolution of uncertainty), and $x_{2,s}$, those to be defined afterwards depending of the state of the world s that finally occurs. The problem described before corresponds to a two-stage stochastic problem, which can be illustrated by the decision tree of Fig. 7:

Notice that contrary to the previous approach, uncertainty does not need to be resolved before starting to take decisions (**act-then-learn** approach). The decisions belonging to the first stage are indeed taken before uncertainty is resolved. Notice also that these decisions are common to the S scenarios. They constitute the hedging strategy. This strategy is defined by minimizing the expected costs (with MARKAL) or maximizing the expected utility (with MM) of all the different states of the world. Let P_s to denote the probability of state-of-nature s . The two-stage stochastic formulation of MARKAL can be as follows, based on the expected system cost $E(Z)$:

$$\begin{aligned} \text{Min } E(Z) &= c_1^T \cdot x_1 + \sum_s P_s \cdot c_2^T \cdot x_{2,s} \quad \text{s.t.} \\ A_0 \cdot x_1 &\leq b_0 \end{aligned}$$

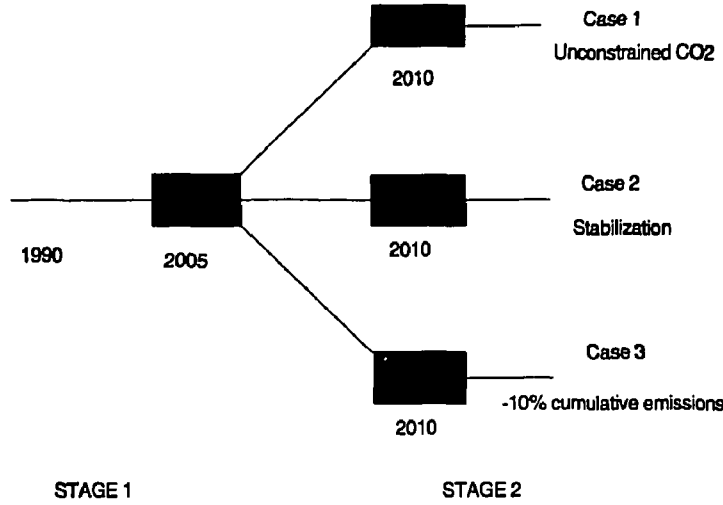


Figure 7: Decision tree for the two-stage stochastic problem

$$A_1 \cdot x_1 + A_2 \cdot x_{2,s} \leq b_s \quad (s = 1, \dots, S) \quad (40)$$

where the constraints are derived from the deterministic (i.e. without uncertainty) formulation of MARKAL, to insure the feasibility of decisions and to link first stage decisions (x_1) with second stage decisions ($x_{2,s}$). This simple formulation, where uncertainty appears only on the right-hand-side b_s , corresponds to the decision tree of Figure 7 describing alternative CO_2 emission reduction policies. Similarly, a stochastic two-stage MM can be formulated based on the expected utility function, $E(U)$:

$$\begin{aligned} \text{Max} \quad E(U) &= \ln C(x_1) + \sum_s P_s \cdot \ln C(x_{2,s}) \quad \text{s.t.} \\ G_0 \cdot x_1 &\leq d_0 \\ G_1 \cdot x_1 + G_2 \cdot x_{2,s} &\leq d_s \quad (s = 1, \dots, S) \end{aligned} \quad (41)$$

Such formulations can be extended to do multi-stage analyses, when all uncertainties are not resolved at the same time. Finally, the multi-objective function of the stochastic model with risk aversion is formulated as:

$$\begin{aligned} \text{Min} \quad E(Z_a) &= c_1^T \cdot x_1 + \sum_s P_s \cdot c_{2,s}^T \cdot x_{2,s} + \lambda \cdot \sqrt{\sum_s P_s \cdot (c_1^T \cdot x_1 + c_{2,s}^T \cdot x_{2,s} - E(Z))^2} \\ A_0 \cdot x_1 &\leq b_0 \\ A_1 \cdot x_1 + A_2 \cdot x_{2,s} &\leq b_s \quad (s = 1, \dots, S) \end{aligned} \quad (42)$$

where λ is a parameter of the multiobjective function that forces solutions with low cost variance (and thus reduces risk). $E(Z)$ is the expected cost as estimated in the two-stage stochastic Markal

problem. The GAMS version of MARKAL has been simplified and formulated as a two stage problem for the Netherlands. The first studies with the Swiss stochastic model are based on the Dutch version of Markal. But, the model modifications undertaken in the Netherlands are not appropriate for Switzerland. This is due to the treatment of the electricity sector that excludes the load profile. Therefore the original version of the model had to be re-established.

6.2 Hedging strategy with MARKAL

As previously mentioned, the scenario-by-scenario analysis does not provide policy makers with a single set of recommendations, such as a unique tax level, to address the climate change issue. The following figure 8 describe the main results obtained based on the deterministic analysis.

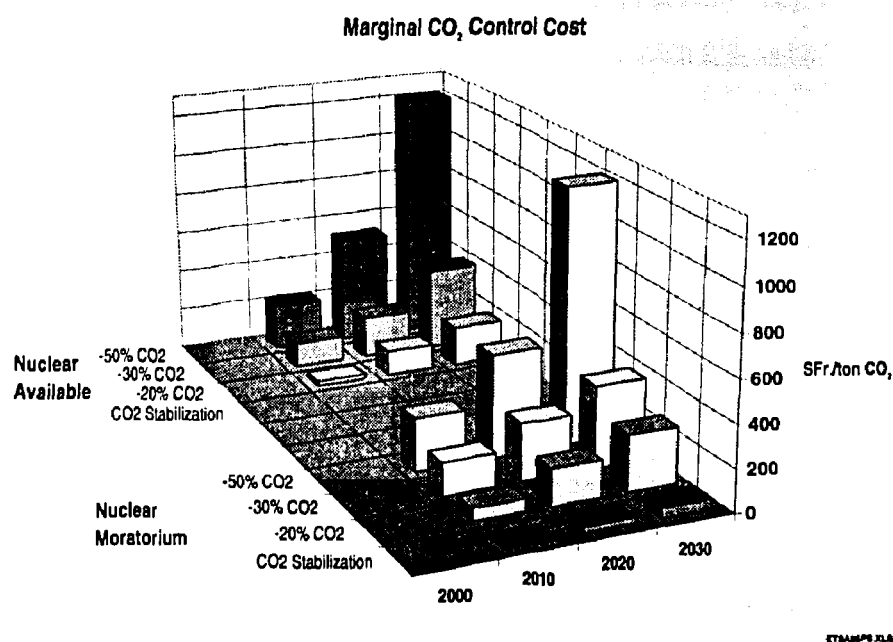


Fig. 8: Deterministic model. Marginal cost estimates per scenario.

A variety of taxes are estimated that depends on the nuclear availability, the level and the rate of reduction. To overcome this drawback, we use a stochastic programming approach to design a strategy to hedge for climate change". A stochastic version of MM being not yet available, we use a two-stage stochastic version of MARKAL. This version has been adapted from Swiss MARKAL (Kyproos, 1990) based on experiments made with the SP/OSL library (King, 1993). We consider three states of the world (SW1, SW2 and SW3, respectively) related to CO_2 emission reduction: baseline (no reduction), stabilization, and a cumulative 20% reduction between 2000 and 2030 (relative to constant 1990 emissions). The last case corresponds to an annual trend of emission reduction of 30% relative to 1990. The assumed probabilities for the three states of the world are 25%, 50% and 25% respectively. We assume furthermore that the uncertainty related to the climate change issue will be revealed by the year 2010. This problem can be described by the decision tree of Figure 7, where the years 1990-95 can be viewed as a calibration period for the model. Three deterministic scenarios have also been considered with the same time-cumulated CO_2 reduction targets as described above: no reduction, cumulative stabilization and 20% reduction (relative to 1990, between 2000 and 2030). The global impact of the decisions taken in the energy system can be evaluated by considering the total emissions of CO_2 over time, see Figure 9.

Notice that in Figure 9, CO_2 emissions for the stochastic case are reported with solid lines and with dashed lines for the deterministic ones. Let us now detail the solution of the stochastic programming model. The hedging strategy between 2000 and 2005 consists in reducing CO_2 emissions down to a level lying between the deterministic stabilization and reduction cases. This is to anticipate possible future reduction and to minimize the costs of adaptation to the state of the world SWi that finally takes place. After 2010, if no reduction is required (when SW1 occurs), CO_2 emissions increase steadily up to the level of the deterministic baseline case. If a cumulative stabilization turns out to be necessary (SW2), CO_2 emissions are however allowed to increase slightly relative to the deterministic stabilization case, because of early reductions made between 2000 and 2005. Finally, if a 20% reduction has to be reached to prevent drastic climate change (SW3), CO_2 emissions are reduced a little more than in the deterministic reduction case, to compensate for the extra emissions of 2000-2005. Another valuable source of information is given by the marginal costs of CO_2 reduction. They correspond to taxes to be imposed on CO_2 emissions to reach the different specified targets (stabilization or reduction), as defined in the pricing and standard approach of Baumol and Oates (1971). Table 8 reports on the undiscounted marginal costs of reduction.

Table 8: Undiscounted marginal costs of CO_2 emission reduction (SFr / t CO_2)

Year	hedging	stabilization	SW2	20% reduction	SW3
2000	38	23		101	
2005	49	30		129	
2010		38	34	165	182
2015		49	43	210	233
2020		62	55	268	297
2025		79	70	343	484
2030		101	90	437	484

For the years 2000 and 2005, the stochastic programming approach computes only one set of

"Most of the results described here are given in the report, O. Bahn, E. Fragnière, S. Kyproos, 1996

marginal costs (column labeled hedging). It corresponds to a tax to be imposed on CO_2 emissions to hedge for climate change. This tax is low and easily acceptable (around 9 to 11 cents per liter of gasoline). Its introduction corresponds to a least regret strategy, which balance present regret of imposing premature and costly emission reduction with future regret of neglected reduction in the past. After the year 2010, when uncertainty about the climate change issue is resolved, taxes are either removed (when SW1 occurs), or adjusted to meet the CO_2 reduction targets (SW2 and SW3).

6.3 Conclusions

The first priority, in the carbon dioxide debate, is to establish a clear and acceptable scientific proof (experimental evidence) concerning the global warming effect and its correlation to the increased concentrations of the greenhouse gases. This is of primary importance because some leading industrialized countries argue that the scientific evidence is not given. In such a situation, they are not yet prepared to initialize expensive policy actions for CO_2 mitigation.

System analysis and integral assessments of the physics, the economics and the technological aspects of the problem are a prerequisite for understanding and structuring the debate on climate sustainability. This report is an effort to document some quantitative results on the possibility to introduce policies against CO_2 . It concludes that even for an industrialized country with very efficient energy system associated with high carbon taxes, enough options are available to drastically reduce carbon taxes and effectively contribute to a sustainable environment.

First, the conclusions based on the deterministic results are discussed and then the results of the stochastic analysis:

6.3.1 Deterministic analysis

The study enhances the conclusion that a combination of policies like carbon taxes in the national level and compensation payments for CO_2 control measures together with a system of international emission rights is a policy that moderates economic implications while satisfying sustainability conditions. How are these conclusions justified?

The results of Markal-Macro for Switzerland indicate that even a uniform percentage reduction of emissions by 50% relative to the 1990's emissions, is feasible from the technical point of view. The economic losses though, due to the restructuring of the Swiss energy system is a considerable fraction of the expected growth. Thus, instead of a 77% increase of economic output by the year 2030, relative to the year 1990, a net growth of 70% is estimated.

The equivalent per capita losses are approximately 3.4 kSFr or 4.5 % of the per capita GDP level. This is probably, from the political point of view, beyond any acceptance. The associated carbon taxes are also very high. The high costs ask for more efficient policies in the national level and cooperation in the international level.

Introducing compensation payments and with the flexibility to trade-off emission reductions among different GHGs, Switzerland can reduce the tax level to a significant extend. This policy on the national level, combined with tradeable emission permits in the international level will further reduce the tax level. (See also, B. Büeler and S. Kypreos, 1996).

6.3.2 Stochastic analysis

Global climate change is an uncertain threat, but a very serious one. The different options to prevent this change from happening can be very costly. MARKAL and MARKAL-MACRO modeling frameworks offer significant insights concerning the economic and engineering dimensions of the climate change issue. In agreement with other studies, we believe that one of the best short term strategies is to buy greenhouse insurance, starting with "no-regrets"¹⁰ options (Manne and Richels, 1992), to remove subsidies and distortions of the energy markets and to introduce voluntary measures, as proposed by the WEC Conference in Tokyo, in 1995.

Simultaneously, technological options that represent long term alternatives to fossil fuels have to be supported, developed and demonstrated. This R & D policy is the best insurance against global warming. The level of carbon tax and the outcome of cost-benefit debate is directly related to the technological progress in these alternative systems. Making, for example, solar electricity cost effective reduces the carbon tax and helps to make CO_2 mitigation policy more acceptable.

A complementary to "no-regrets" policy would be to introduce low level and reversible taxes (i.e., the "minimum regrets" option as estimated by the stochastic programming approach). With this, we could gain time to resolve uncertainty, and to select and proceed with better technical choices, since alternative technologies will become available. In the longer term, if the threats are confirmed, efficient policy shall be based on international cooperation. Otherwise, if the climate change threats are not confirmed, the low level taxes can be canceled without regretting the loss of premature commitments to costly abatement strategies.

¹⁰"No-regrets" measures are those whose benefit, such as reduced energy cost and reduced emissions of local and regional pollutants equal or exceed their cost to society, excluding the benefits of climate change mitigation.

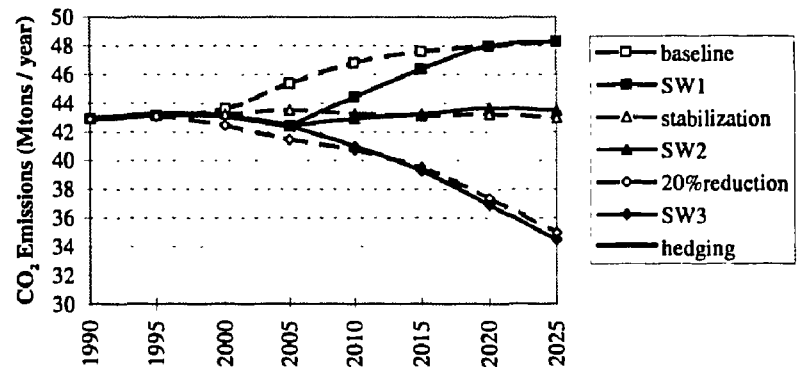


Figure 9: CO₂ emission paths for stochastic and deterministic cases

7 Appendix A; The MARKAL Stand-alone Model

7.1 Summary

This Appendix gives a detailed mathematical formulation of the energy allocation model MARKAL. The model is applied to study the problem of energy supply for Switzerland under different policy constraints. MARKAL¹¹ is a time-phased L.P model which is structured around a representation of the Reference Energy System (RES) of a country. The variables of the model characterize the various energy forms from the primary production to the end-use devices, the sources of energy supply to the energy system and the installed capacities of the different technologies.

The following Fig. App-1, represents, in a schematic way, the energy flows of the model. The model equations describe the balance of energy carriers, the capacity build-up, the load management for electricity, and the use of resources.

The objective function of the model refers to the discounted energy system cost for the time horizon of the analysis. Other objective functions could be specified describing the oil imports, the use of renewables and the atmospheric emissions. Multi-objective analysis is a usual technique applied to define the trade-off between different objectives. The introduction of a carbon tax on fossil fuels is discussed at the end of the chapter, that allows to specify control of CO₂ emissions to a desired policy level. One could state that the **model balances the energy, materials, and emissions as well as the capital and labor associated with the operation and expansion of the energy system based upon a multi objective decision making approach. This normative approach defines optimal use of resources and respects the environmental concerns. Linking MARKAL with a macroeconomic growth model we can estimate the economic implications of different policies related to energy and the environment.**

The model distinguishes among technologies and the system sources of supply.

The sources of supply cover all possibilities by which energy can enter or leave the system. This includes imports, exports and mining. Another possibility exists which allows to stockpile a resource in one period to be used in a subsequent period.

Technologies are divided to three groups:

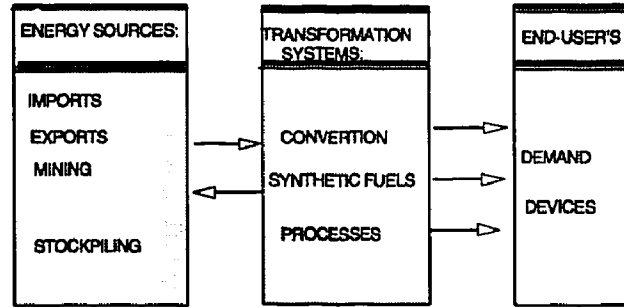
- Processes: which convert one or more energy inputs to different energy outputs.
- Conversion systems: for electricity generation and/or heat.
- Demand devices: which compete to satisfy the end-user's energy markets.

7.2 Indexes, variables and equations

It follows a mathematical description of the model equations through a set of indexes, variables and parameters. The exact description given in Fishbone, 1983. The purpose of the description given here is to define the most important characteristics of the model without getting lost into

¹¹ MARKAL has been mainly developed at BNL, USA and KFA-Jülich, in Germany for the IEA Energy Technology System Analysis Project. The specification of the model equations and its data base is the outcome of many technical meetings among the project participants. The participants have discussed, modified and tested the model in a series of studies. The first Swiss version of MARKAL has been implemented under the VAX-VMS operating system. A data base with technology description and the demand simulation model SMEDE, both developed at PSI, generate the input data for MARKAL. The newest version of the model is running under the Markal User's Support System (MUSS) on PC's and it has been developed at BNL.

REFERENCE ENERGY SYSTEM



MARKALOPR

Fig. App-1. Energy flows in MARKAL

details. The option of stockpiling energy fuels with period -to- period flow lags (for example fabrication/reprocessing of nuclear fuel) is not described here. We don't describe also storage systems and processes with variable outputs. The important model improvements related to regionalization, material flows and the introduction of demand device specific load characteristics is not described here.

7.2.1 Indexes

- $t = 1, \dots, T$ is the period index, (usually periods of five years are assumed);
- $h = 1, \dots, H$ is the year division index: (summer-day, summer-night, winter-day, winter-night, intermediate-day, intermediate-night).
Accordingly, the time duration of each division of the year is given by the parameter δ_h , i.e. duration of winter-day = $1/2 * 2/3$, of winter-night = $1/2 * 1/3$, etc.

- Technology indexes:

$p = 1, \dots, P$ is the technology index for processes;

$\epsilon = 1, \dots, E$ is the index for electricity production technologies other than combined power and heat systems with pass-out or back pressure turbines;

$\nu = 1, \dots, N$ is the index for combined power and heat systems with pass-out turbines;

$\nu' = 1, \dots, N'$ is the index for combined power and heat systems with back-pressure turbines;

$\theta = 1, \dots, \Theta$ is the index for heat production technologies;

$d = 1, \dots, D$ is the index for demand devices;

$d^m = 1, \dots, D^m$ refers to all devices existing in market m ;

- $r = 1, \dots, R$ is the index for all technologies included in the model, and we have the relation $R = P + E + N + N' + \Theta + D$;
- $m = 1, \dots, M$ is the index for the different demand categories;
- $j = 1, \dots, J$ is the index of energy carriers;
- $s = 1, \dots, S$ is the index for the system energy sources i.e. imports, exports, mining and stockpiling of energy carrier;
- $k = 1, \dots, K$ is the index representing the steps of the linear cost-supply function of energy sources;
- $i = 1, \dots, I$ is the index of the different emissions accounted in the model.

7.2.2 Model variables

- Capacity variables (stock):

Y_{rt} added capacity (investments) at time period t , technology r ,

Z_{rt} total installed capacity at time period t , technology r ,

- Activity variables (flow):

X_{pt} Annual production of process p , at time period t .

E_{cht} Electricity production of plant ϵ , period t time division h .

M_{cht} 'Maintenance' of plant ϵ , period t time division h

$H_{\theta ht}$ Heat production of heating plant θ . period t time division h .

$H_{\nu ht}$ Heat production of pass-out (POT) plant ν , period t , time division h .

- Sources of energy supply:

W_{sjkt} Annual energy flow of energy carrier j , related to source s , step k of the supply-price curve of energy carrier j , period t . The user defines in the dictionary file a combination of these indexes which are appropriate to represent the specific situation of a country.

The heat production of back-pressure turbines is represented as a fraction of the electricity production variable, since it exists a constant relation between electricity and heat production. The electricity production of Pass-Out Turbine (POT) plants, on the other hand, is represented by a complex relation invented to reduce the number of constraints required to define such systems:

$$E_{\nu ht}^{real} = E_{\nu ht}^{model} + H_{\nu ht} * hc_{\nu h} * (1 - m_{\nu}) / m_{\nu} \quad (43)$$

The parameters and the justification of this expression will be explained later on.

7.2.3 Description of equations

- **Capacity transfer constraint:** These inter period constraints ensure that the total installed capacity of a technology in a period equals the residual capacity and the sum of investments done in the previous periods and within the life time of a technology. $\forall t, r$

$$Z_{rt} = \zeta_{rt} + \sum_{m=t-l_r+1}^t Y_{rm} \quad (44)$$

l_r represents the technical and economic life time of technology r .

the parameter ζ_{rt} represents residual capacity at time period t , technology r , that contributes to the system cost by only its O&M costs.

- **Demand balance:**

The model is driven by a set of exogenous constraints defining the development of energy demand DM_{mt} as function of time.¹² **This constraint ensures that for each demand category m and for each time step t , the sum of installed capacity of devices competing in that market, exceeds or equals demand DM_{mt} .**

$$\sum_{d^m=1}^{D^m} \omega_{d^m m} Z_{d^m t} \geq DM_{mt} \quad (45)$$

The index d^m refers to all devices supplying energy in market m i.e. $\forall d^m \in \{1, \dots, D^m\}$

The parameter $\omega_{d^m m}$ defines the fraction of energy output of demand device d^m which satisfies demand category m . Usually the fraction is equal to 1, but some times a device could satisfy two different demands.¹³

- **Fuel balance other than electricity and heat:**

The sum of imports, mining and production of an energy carrier should be equal or exceed its consumption. The equation is valid for each time step t and for each energy carrier j .

¹²These constraints are defined either by using the engineering simulation model SMEDE or the MACRO submodel in the MARKAL-MACRO model. The demand for the transportation sector is given as $10^6 \text{ vehicle} * km$ and it is transferred to energy use by the efficiency of the vehicle expressed as km/GJ . Other demands are defined as $PJ/year$ of useful energy.

¹³This constraint should have been an equality. A usual technique to reduce convergence time is to define it as a non-equality, and let the optimization procedure to reduce the extra (slack) capacity to zero.

$\sum_{sk} W_{sjkt} * tr_j$	net production of fuel j by source s , step k
$+ \sum_p X_{pt} * tr_j * \gamma_{pjt}$	production by process p
$+ \sum_{ph} E_{cht} * tr_j * \gamma_{ejt}$	by-product j of conversion plant e
$\geq \sum_p X_{pt} * \beta_{pjt}$	consumption by process p
$+ \sum_{s, kk, jj} W_{sj, jj, kkt} * \beta_{s, j, jj, t}$	consumption of fuel j by mining fuel jj , step kk
$+ \sum_{eh} E_{cht} * \beta_{ejt} * tr_j$	consumption by electrical plant e or v or v'
$+ \sum_{\theta h} H_{\theta ht} * \beta_{\theta jt}$	consumption by heating plant θ
$+ \sum_{vh} H_{vht} \beta_{vjt} h_{evh} (1 - m_v) / m_v$	consumption by pass-out plant v
$+ \sum_d Z_{dt} / \eta_{dt} * \beta_{dj t}$	consumption by demand device d

tr_j is the transmission/distribution efficiency of energy carrier j from source to consumption.

γ_{pjt} is the fractional process output to fuel j per unit of process activity.

γ_{ejt} is the by-product output fuel j relative to electricity output.

β_{pjt} is the fractional input of fuel j per unit of process activity.

β_{ejt} is the fractional input of fuel j per unit of electricity production.

β_{vjt} is the fractional input of fuel j per unit of electricity production.

$\beta_{dj t}$ is the fractional input of fuel j per unit of demand capacity.

$\beta_{s, j, jj, t}$ is the fractional input of fuel j for mining fuel jj

η_{dt} is the efficiency of demand device d .

Important is to remember that, even for coupled production plants the fractional inputs β are defined relatively to the electricity output.

• **Electricity balance:**

$\forall h, t, j = \text{electricity}$

$\sum_{sk} W_{sjkt} * tr * \lambda_{sh}$	electricity imports minus exports, step k
$+ \sum_{\epsilon} E_{\epsilon ht} * tr$	production by plant ϵ
$+ \sum_{\nu'} E_{\nu' ht} * tr$	production by plant ν'
$+ \sum_p X_{pt} * \gamma_{pjt} * tr$	production by process p
$+ \sum_{\nu} [E_{\nu ht} + H_{\nu ht} h c_{\nu h} (1 - m_{\nu}) / m_{\nu}] tr$	production of pass-out plant ν
$\geq \sum_p \delta_h * \beta_{pjt} * X_{pt}$	consumption of electricity by process p
$+ \sum_{mdm} \lambda_{mh} \beta_{dmjt} \omega_{dm} Z_{dmt} / \eta_{dmt}$	consumption by demand devices d
tr_j	is the transmission/distribution efficiency of energy carrier j
λ_{mh}	defines the load fraction of demand m in time division h .
λ_{sh}	defines the load fraction of source s in time division h .
tr	means the transmission/distribution efficiency of electricity.
δ_h	is the duration of time division h .

- The district heat balance is similar to the electricity balance:

District heat balance: $\forall h, t \quad j \in \text{dist. heat}$

$\sum_{\theta} H_{\theta ht}$	production by heating plant θ
$+ \sum_{\nu} H_{\nu ht} * tr_j$	production of pass-out plant ν
$+ \sum_{\nu'} E_{\nu' ht} * tr_j / r_{\nu'}$	production of back-pressure plant ν'
$\geq \sum_{mdm} \lambda_{mh} \beta_{dmjt} \omega_{dm} / \eta_{dt} * Z_{dmt}$	consumption by demand devices.
λ_{mh}	defines the head load fraction of demand m in the time division h ,
tr_j	means the transmission/distribution efficiency of district heat,
$r_{\nu'}$	defines the electricity to heat ratio for the back-pressure turbine.

- **Load management constraints; Peaking constraint:** ¹⁴

This constraint ensures that enough capacity exists to meet peaking requirements at the time division with the greatest load.

¹⁴The peaking constraint should also include the contribution of imports and exports. It would have been more appropriate to include another peaking constraint and force the peaking plants to satisfy the peaking fraction of electricity consumption. This needs to define for each demand device consuming electricity the portion of demand that corresponds to the peaking load.

The model includes a "base load" constraint where a fraction (95%) of the night electricity is produced by base load plants. The heating sector assumes similar to electricity peaking constraints.

$$\frac{tr * \sum_i Z_{cht} * pf_{ei}}{(1 + RM)} + \frac{tr * \sum_i E_{e,ht} * pf_{e,}}{(1 + RM) * \delta_h} \geq \frac{\sum_{mdm} \lambda_{mh} * \beta_{d^{mdm}} * \omega_{d^{mdm}} * Z_{d^{mdm}}}{(\eta_{dt} * \delta_h)} + \sum_p X_{pt} * \beta_{pte} \quad (46)$$

Parameters pf_{ei} and $pf_{e,}$ define the fraction of installed capacity which can be allocated to load (renewables have a coefficient less than one). The second term is optional and refers to peaking plants e which are taken into account by their production and not by their capacity. The factor $(1 + RM)$ refers to reserved capacity necessary to meet the electric load at the time of highest demand. The factor increases the average load estimated by the model (right-hand-side of equation), in order to compensate for peak and reserve margin.

As indicated in Fig. App-2 we have:

$$1 + RM = \frac{\text{INSTALLED CAPACITY}}{\text{AVERAGE DAY LOAD}}$$

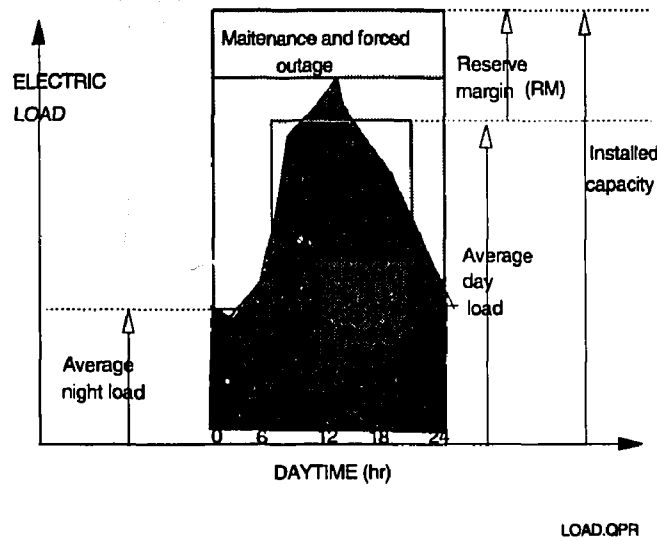


Fig. App-2: Load curve for the day of highest load and the RM factor as defined in Markal

- Plant utilization:

This constraint ensures that the plant maintenance is less than or equal to the plant unavailability minus forced outage.

The model has the option to allocate maintenance M_{cht} to seasons of low demand.

The user has either to define explicitly the seasonal availability of electricity production i.e. α_{cht} as it is the case for photovoltaic plants, or to define an average annual availability α_{et} and the fraction of plant unavailability due to forced outage (α_e).

In that case the model allocates maintenance to seasons, $\forall c, t$, according to:

$$\sum_h M_{cht} \leq Z_{ct} * (1 - \alpha_{ct}) * (1 - o_c) \quad (47)$$

- **Seasonal Plant availability (production):**

This constraint ensures for each plant, that the electricity production in each time division is less or equal to the available capacity minus scheduled maintenance.

If availability is given by time division, i.e. by α_{cht} , then:

$$E_{cht} \leq Z_{ct} * \delta_h * \alpha_{cht} \quad (48)$$

Otherwise, if availability is given annually, i.e. α_{ct} , then:

$$E_{cht} + M_{cht} * \delta_h \leq Z_{ct} * \delta_h * \alpha_{ct} * [1 - (1 - \alpha_{ch}) * o_c] \quad (49)$$

In the case of pass-out plants we have, respectively:

$$E_{vht} + H_{vht} * hc_{vh}/m_v \leq Z_{ct} * \delta_h * \alpha_{cht} \quad (50)$$

or,

$$E_{vht} + H_{vht} * hc_{vh}/m_v + M_{vht} * \delta_h \leq Z_{vt} * \delta_h * \alpha_{vt} * [1 - (1 - \alpha_{vh}) * o_c] \quad (51)$$

Similar equations i.e. $X_{pt} \leq Z_{pt} * \alpha_{pt}$ are valid for processes.

- **Bounds on technology implementation and resource use:** The user could specify bounds according to the following constraints:

$$Y_{rt} \leq b_{rt} \quad (52)$$

$$Z_{rt} \leq b'_{rt} \quad (53)$$

$$Z_{rt} \leq Z_{r,t-1} * g_{r,t-1} + b_r \quad (54)$$

The first two equations refer to direct bounds on investments and capacity, respectively, and the third one refers to bounds on technology implementation rate. This equation allows to simulate technology implementation growth, if a technology is competitive, in order to reach a pre specified upper bound B_r in NP periods, starting from an installed capacity of b_r and an average growth g . The initial technology penetration is:

$$b_r = B_r * g / [(1 + g)^{NP+1} - 1] \quad (55)$$

The cumulative resource bound is formulated as an inter period constraint:

$$\sum_{tk} W_{stjk} \leq R_{js} \quad (56)$$

- **Group constraints:**

The user has the flexibility to introduce any relation between the model variables in order to define specific futures of the system not already included in the basic structural equations of the model.

$$\sum_r Z_{rt} * a_{rt} + \sum_p X_{pt} * a_{pt} + \dots + \sum_c E_{ct} * a_{ct} \leq b_{rt}^* \quad (57)$$

A typical example for Switzerland is the electricity use for heating systems which is restricted either by law or due to the existing capacity of the distribution network.

7.3 Emission and material balances

The material and emission balance constraints are quite similar to the energy balances. A set of non-binding (accounting) equations balance the emissions related to the construction, operation and the final disposal of the different technologies included in the Reference Energy System of a country. Only the direct emissions are considered. The accounting of indirect emissions is quite possible but it needs extra information related to the I/O balances of a country.

The approach to balance emissions is simple: some coefficients, included in the data-base, describe the amount of emissions released per unit of energy use associated with a technology. The user has also the option to include the emissions related to new investments and to the imports/exports of fuels. Similar to emission balances, material balances can also be introduced that specify the transformation of materials through the investments, operation, or the final disposal of existing capacity. (See C. Berger 1990).

All it is needed is to specify in the technology data-base of the model the material requirements per unit of activity (investments, production and final disposal), and to include the pollutants or materials in the appropriate set definition of the model.

Anyhow, the best utilization of the emission and material accounting constraints is obtained by including in the RES abatement options and alternative technologies for material use or recycling (D. Gielen, P. Oken, 1993). This allows to formulate environmental policy goals on pollutants and obtain material recycling by including these balance constraints as partial objectives in the multi-objective decision making framework of the model.

Emission balance:

The emissions for pollutant i , are estimated based on all model variables e.g. capacity, investments and activity variables, and their specific emission coefficients. It is the responsibility of the model user to define the input coefficients such that double counting of pollutants is not possible. The annual emissions for each time step t and for each pollutant i are:

Em_{it}	total emissions by time step t and pollutant i
$\sum_{sjk} W_{sjkt} * tr_j * \epsilon_{sjkt}$	net emissions of pollutant i , of fuel j by source s , step k
$+ \sum_p X_p * \epsilon_{pit}$	activity by process p times emissions i per unit of activity
$+ \sum_{eh} E_{eht} * \epsilon_{iet}$	emissions by electrical plant e or ν or ν'
$+ \sum_{\theta h} \epsilon_{i\theta t} * H_{\theta ht}$	emissions by heating plant θ
$+ \sum_{\nu h} H_{\nu ht} \epsilon_{i\nu t} h c_{\nu h} (1 - m_\nu) / m_\nu$	emissions by pass-out plant ν
$+ \sum_d Z_{dt} / \eta_{dt} * \epsilon_{dit}$	emissions by demand device d
$+ \sum_k Y_k * \epsilon_{kit}$	emissions i , per unit of investments * investments on technology k

7.4 The objective functions of the model

The most commonly used function is the function price, $\mathcal{Z}$, which is the discounted sum of three functions, the investment cost I_t , the annual cost A_t and the salvage cost S_t . This function is the most complex relation defined in the model.

- Investment cost

$$I_t = \sum_r Y_{rt} * sc_{rt} \quad (58)$$

The parameter sc_{rt} is the specific investment cost per unit of capacity.

- Annual cost

$$\begin{aligned}
 A_t = & \sum_{sjk} p_{sjkt} * W_{sjkt} \\
 & + \sum_{s,j,j,k} del_{jj,st} * \beta_{s,j,jj,kt} * W_{sjkt} \\
 & + \sum_r Z_{rt} * fom_{rt} \\
 & + \sum_{dj} Z_{dt} * (\beta_{dj t} * del_{dj t} + v_{dt}) / \eta_{dt} \\
 & + \sum_{pj} X_{pt} * (\beta_{pj t} * del_{pj t} + v_{pt}) \\
 & + \sum_{ehj} E_{eht} * (\beta_{ej t} * del_{ej t} + v_{et}) \\
 & + \sum_{\theta hj} H_{\theta ht} * (\beta_{\theta j t} * del_{\theta j t} + v_{\theta t})
 \end{aligned}$$

$$\begin{aligned}
& + \sum_{\nu h j} E_{\nu h t} * (\beta_{\nu j t} * del_{\nu j t} + v_{\nu t}) \\
& + \sum_{\nu h j} H_{\nu h t} * hc_{\nu h} * (1 - m_{\nu}) / m_{\nu} * (\beta_{\nu j t} * del_{\nu j t} + v_{\nu t})
\end{aligned}
\tag{59}$$

The parameters are:

p_{sjkt} : the price of fuel j , source s , step k , time step t .

del_{rjt} : the delivery cost of fuel j , to technology r , time step t .

fom_{rt} : the fixed o&m cost of technology r , time step t .

v_{rt} : the variable o&m cost of technology r , time step t .

The specific cost, the fixed o&m cost and the variable o&m cost for electric plants or district heating plants, include the transmission and distribution cost of the grid.

These grid-costs are explicitly defined in the data base of the model.

• Salvage cost

The understanding of salvage cost is associated with the concept of annualized capital recovery factor, CR_l . This factor represents the amount of money needed per annum to cover fixed capital charges i.e., interest and amortization of an initial expenditure (investment) and within a given number of years, i.e. l .

The MARKAL function "investments" I_t charges for each new capacity Y_{rt} installed in period t , the full initial investment cost $Y_{rt} * sc_{rt}$. This is equivalent of charging to the system cost at period t the present worth value of fixed capital charges, CR_l , for all subsequent years until the life of investments l_r expires.

The situation becomes complex when the time horizon of analysis expires before reaching the end of the life time of investments. These extra charges for the period after the end of the time horizon, are the 'salvage costs' and they should be subtracted from the system costs. In the following, the salvage formula is estimated following the amortization of an initial debt, year by year. If S_0 is the initial investment, d the interest rate, CR_l the capital recovery factor in l years, and S_n the remaining debt at the end of n^{th} year, then we have:

$$S_1 = S_0 * (1 + d) - CR_l * S_0 \tag{60}$$

$$S_2 = [S_0 * (1 + d) - CR_l * S_0] * (1 + d) - CR_l * S_0 \tag{61}$$

$$S_n = S_0 * (1 + d)^n - CR_l * S_0 \sum_{k=0}^{n-1} (1 + d)^k \tag{62}$$

$$S_l = S_0 * (1 + d)^l - CR_l * S_0 \sum_{k=0}^{l-1} (1 + d)^k \tag{63}$$

Since at the end of the horizon, $S_l = 0.0$, the last equation can be solved for the CR_l i.e.

$$CR_l = (1 + d)^l * d / [(1 + d)^l - 1] \tag{64}$$

In the case that n represents the end of the time horizon then the term S_n is the salvage cost and it must be subtracted. Prior to subtraction, the salvage cost must be discounted back to the year when the investments were made. The definite formula is as follows:

$$S_t = \sum_{rt} Y_{rt} * sc_{rt} * df_t'' * [1 - (1 + d)^{-ypp * (t + l_r - T - 1)}] / [1 - (1 + d)^{-ypp * l_r}] \quad (65)$$

Where, ypp are the years per period (usually five), df_t'' is the discounting factor, i.e. $df_t'' = (1 + d)^{-ypp * (T - t + 1)}$, and l_r is the economic life time of technology. This formulation is very complex. A more elegant solution is obtained in MARKAL-MACRO. In this model only the annualized capital recovery costs CR_t of new investments are considered year by year and thus the salvage cost becomes meaningless !

- The objective function price, $\mathcal{Z}$

The function "price" is the discounted sum, to the beginning of the time horizon, of the three functions discussed before. There is a difference in discounting the annual cost and the investment costs. The annual costs are first discounted to the beginning of a period, by the factor df_0 , and then to the beginning of time horizon, by df_t . We also assume that investments take place at the beginning of a period. We have the relations :

$$df_0 = \sum_{k=0}^{k=ypp-1} (1 + d)^{-k} \quad (66)$$

$$df_t = (1 + d)^{-ypp * (t-1)} \quad (67)$$

$$\mathcal{Z} = \sum_t I_t * df_t - \sum_t S_t * df_t + \sum_t A_t * df_0 * df_t \quad (68)$$

7.5 Multi objective analysis

The model defines other objectives, like:

- **Security $\mathcal{S}$** , which is the cumulative sum of weighted fossil fuel use. The most simple version of 'Security' is the cumulative oil use.
- **Renewables $\mathcal{R}$** , which is the cumulative use of renewable resources.
- **Environment $\mathcal{E}$** , which is the cumulative emissions of different pollutants i.e. NO_x or CO_2 , etc.
- **Qslope** represents a family of functions which is a linear combination of two objectives.

A typical example of 'Qslope' is the function:

$$Q = \mathcal{Z} + \pi * \mathcal{S} \quad (69)$$

One could perform parametric analysis minimizing Q at different values of π , i.e. the slope of Q . A value π^* of the slope could be found, in the feasible space of (Z, S) , which defines a desirable 'Security' level, S^* .

It can be shown that the minimization of Q at π^* , gives the same results as the minimization of Z , when an increased oil price schedule is assumed, according to:

$$p'_t = p_t + \pi^* * (1 + d)^t \quad (70)$$

(t represents the year and not the period). The price increase $\pi^* * (1 + d)^t$, could be interpreted as the necessary oil tax able to obtain a 'security level' S^* , at optimal energy system costs.¹⁵

A similar application is possible in the CO_2 control problem, which allow to specify the carbon tax necessary to fulfill, at optimum, a given cumulative reduction of CO_2 emissions.

$$Q_{CO_2} = Z + \pi * \mathcal{E}_{CO_2} \quad (74)$$

The CO_2 emissions, (excluding CO_2 abatement systems) could be estimated as:

$$\mathcal{E}_{CO_2} = \sum_{it} F_{it} * \epsilon_i \quad (75)$$

Where, F_{it} is the primary fossil fuel use and ϵ_i , is the corresponding specific emission coefficient in $kgCO_2/GJ$.

In a similar way to 'security', the carbon tax necessary to obtain a reduction of emissions to a desired level, could be defined out of the slope π^* which corresponds to the given policy goal, i.e. $\mathcal{E} = \mathcal{E}_{Toronto}$, the carbon tax is:

$$p'_{it} = p_{it} + \pi^* * (1 + d)^t * \epsilon_i$$

The procedure to estimate the appropriate coefficient π^* is obvious: A parametric analysis must be done, performing a set of optimizations, with different price schedules until the cumulative reduction of CO_2 emissions satisfies the policy goal. The selected value of the parameter π^* depends upon the structure of the energy system, the technological options available and the policy constraints imposed i.e. the availability of the nuclear energy, etc.

¹⁵The optimization problems of Q and Z are quite similar. They have exactly the same constraints and similar objective functions. The only difference appears in the specification of their annualized cost of resource use. Assuming that Z_{rest} defines the common part of the objective functions, then we have:

$$Q = Z_{rest} + \sum_{skjt} p_{skjt} * W_{skjt} * df_t + \pi * \sum_{skjt} W_{skjt} \quad (71)$$

or,

$$Q = Z_{rest} + \sum_{skjt} (p_{skjt} + \pi/df_t) * W_{skjt} * df_t \quad (72)$$

Therefore $Q = Z'$ at

$$p'_{skjt} = p_{skjt} + \pi * (1 + d)^t \quad (73)$$

7.6 The pass-out turbines

The pass-out turbine (POT) produces heat by “passing steam out” of the low stage turbine to a heat exchanger and thus to a district heating network. The POT could operate following the load demand for heat and thus reducing part of the electricity production. MARKAL allows to optimize the mode of operation of POT plants according to the load changes. The electricity production takes values within the shaded part of the following Fig.App-3, and under three constraints:

- Below line (A), since the maximum feasible quantity of superheated steam passing through the high pressure stage is limited.
- Above line (B), which limits the heat production, since enough steam should pass the low stage of the turbine to cool the rotor.
- Left to line (C), limited by the size of the heat exchanger.

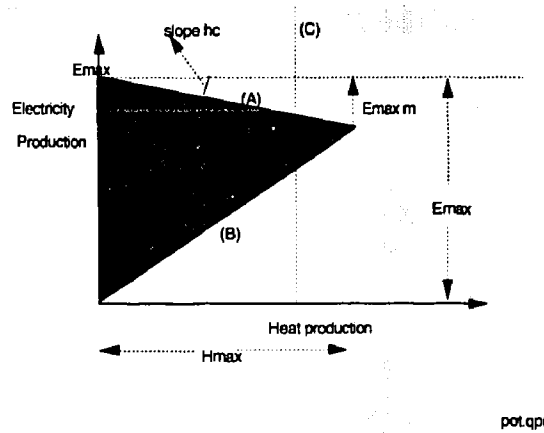


Fig. App-3: Area of possible operation of pass-out turbines

Using the following definitions $hc = \Delta E_{max} / H_{max}$ i.e., the slope of line (A), and $m = \Delta E_{max} / E_{max}$, the maximum fractional losses of electricity, and assuming that condition (C) is not limiting, we can estimate that the electricity production should be above line (B) (first constraint), and below line (A), i.e., within the shaded part of the figure.

$$E \geq H * (1 - m) / m * hc \quad (76)$$

$$E \leq E_{max} - H * hc \quad (77)$$

Introducing now a new variable for electricity, $E' = E - H * (1 - m) / m * hc$, we get the relation $E' \geq 0.0$, which is always satisfied in L.P problems, and the known availability constraint.

$$E' + H * hc / m \leq E_{max} \quad (78)$$

8 Appendix B; Sensitivity Analysis

8.1 Scenarios analyzed with the US data base

Due to the uncertainty associated with the specification of the basic model parameters a sensitivity analysis is performed, changing the values of ESUB, and AEEI¹⁶. Some conservation options are also introduced as end-use technologies in the residential sector. It follows a list of scenarios studied while the main results are presented and discussed below. The work described here has been accomplished during my visit at the Brookhaven National Lab., USA in 1992. The analyzed scenarios are:

- HGDP : The basic reference case using the available data for MM, the so-called US demo case. The parameters used are, ESUB=0.5 and AEEI=0.0
- HAEE : This case is as the previous one but the AEEI=0.5% per year
- HESU : This case is as the previous one, e.g., AEEI=0.5% / year, but ESUB=0.3
- HCON : This case corresponds to HGDP with one exception. A very efficient but expensive conservation technology is introduced in the residential space heat sector R1. This technology is competitive only due to the CO₂ constraint and no competitive in the unconstrained case.

Matrix of cases analyzed

name	ESUB	AEEI	Conservation Potential
HGDP, CO ₂ unbounded	0.5	0.0	low
HGDP, -20 % CO ₂	0.5	0.0	low
HAEE, CO ₂ unbounded	0.5	0.005	low
HAEE, -20 % CO ₂	0.5	0.005	low
HESU, CO ₂ unbounded	0.3	0.005	low
HESU, -20 % CO ₂	0.3	0.005	low
HCON, CO ₂ unbounded	0.5	0.0	high in R1
HCON, -20 % CO ₂	0.5	0.0	high in R1

The 20 percent reduction of CO₂ emissions refers to the 1990's level of emissions.

8.1.1 Autonomous efficiency improvement, AEEI

There follows a short description of the results with some conclusions:

¹⁶In the year 1992 the term AAEI was used instead of DDF.

Sensitivity analysis on AEEI				
AEEI =0.0 AEEI =0.5 % /year				
demand level for residential heat (R1)				
	1990	2020	1990	2020
Unconstr.	4.5	8.	4.5	8.0
-20% CO2	4.5	6.4	4.5	6.3
marginal cost of residential heat demand \$/GJ				
	1990	2020	1990	2020
Unconstr.	9.8	12.1	9.5	10.8
-20% CO2	9.1	16.6	9.1	17.
Total demands in Exajoules				
	1990	2020	1990	2020
Unconstr.	60.67	108.9	60.67	104.74
-20% CO2	60.67	83.19	60.67	81.732
GDP in Trillion dollars				
	1990	2020	1990	2020
Unconstr.	3.542	7.081	3.542	7.328
-20% CO2	3.542	6.822	3.542	7.068
marginal cost C-tax dollar/ton C				
	2020		2020	
	327		327.8	

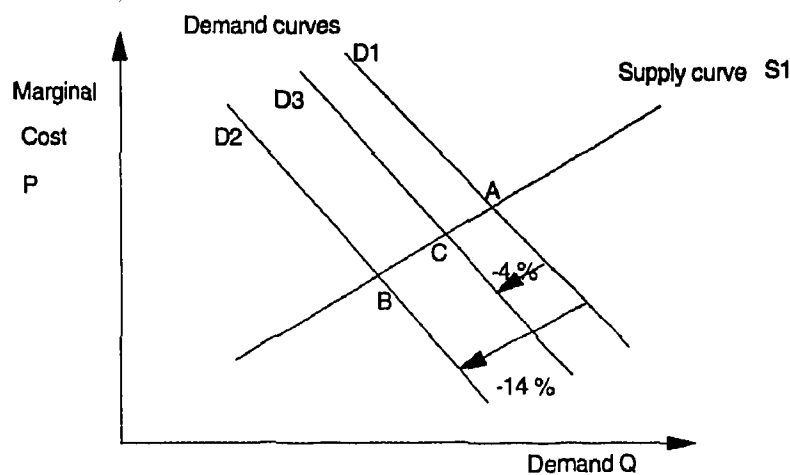
The AEEI factor allows to study different scenarios by taking into account exogenous, independent of prices trends in energy efficiency. An annual improvement of efficiency by 0.5 percent has significant influence to the overall results.

The relation $d_{aeei,t} = d_t * e^{-aeei*t}$, when applied for AEEI=0.005 and thirty years, should have reduced useful demands by 14%, if everything else was constant. The actual reduction of demands is only 4%. The difference between the expected and the estimated demands is explained due to the induced higher economic growth and the changes in the marginal cost of demands.

The AEEI factor "makes energy inexpensive" in the sense that the "Gross Output" needs less energy to be produced. The induced economic growth due to efficiency improvement (at no extra costs) is 3.5 percent by the year 2020. This GDP growth shifts demand to a higher level than the estimated value, when all other model variables would have been constant. The GDP-shifted demand remains anyhow lower than the equilibrium demand at AEEI=0.0. This demand reduction

is associated with lower (or equal) marginal costs per unit of demand. (a lower demand could be satisfied by either the same marginal technology or by the next less expensive one). Due to the reduced price of demands the equilibrium value of demand is again increasing. Finally, equilibrium is obtained at 4 percent less demand than in the case with $AEEI=0.0$.

This behavior is illustrated in the following figure.



The equilibrium point A moves to C. It should have been at B if all other model variables were constant.

ESUB.QPR

Fig. B1: "Autonomous efficiency improvement" and difference between partial and general equilibrium results

8.1.2 Elasticity of substitution

The next parameter modified is the elasticity of substitution. The definition of ESUB is: $\sigma = \frac{\partial \ln(Y/E)}{\partial \ln(P_e/P_{c,l})}$. If $ESUB=0.5$, 1% change in the relative ratio between value added (capital-labor pair) and energy, needs a 2% change in the relative price ratio (denominator). For $ESUB=0.30$, 1% change in the nominator needs a relative price ratio change of 3.33%. (Therefore, reducing ESUB we make more difficult to substitute energy by capital and labor)

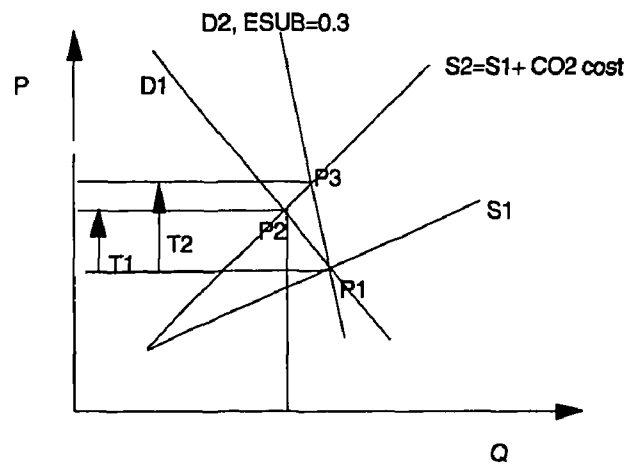
Sensitivity analysis on ESUB
ESUB has been reduced to 0.3 from 0.5

		ESUB=0.5	AEEI=0.5%	ESUB=0.3	AEEI=0.5%
Total demands in Exajoules					
		1990	2020	1990	2020
Unconstr.		60.67	104.74	60.67	104.02
-20% CO2		60.67	81.73	60.67	81.42
GDP in Trillion dollars					
		1990	2020	1990	2020
Unconstr.		3.542	7.328	3.542	7.316
-20% CO2		3.542	7.068	3.542	6.958
GDP loss	by 2020		3.5 %		4.9%
marginal cost C-tax dollar/ton C					
		2020		2020	
		327.8		442.6	

Examining the results we realize that the CO_2 control cost is sensitive to ESUB while energy demand and GDP change at a lower rate. One conclusion is important, the level of tax is a function of ESUB and thus the value of the elasticity of substitution to be adopted in the analysis needs a good justification.

A reduced value in ESUB means that it is more difficult to substitute for energy by using capital and labor. This explains the reduced growth. The question is how the higher carbon taxes, in the CO_2 constrained cases, can be explained?

This reaction of the model is illustrated in Fig. B2. D_1 is the demand curve at $\sigma = 0.5$. The equilibrium point is at P_1 . Introducing a carbon constraint, the cost of supplying energy increases and the equilibrium moves to P_2 , i.e., at lower demand and higher price. The tax corresponding to this situation is T_1 . With a lower elasticity of substitution, the demand curve D_2 , becomes more steep, the equilibrium point moves to P_3 and the tax increases. Energy use increases.



P1: Equilibrium without CO2 control

P2: Equilibrium with CO2 control, $ESUB=0.5$

P3: Equilibrium with CO2 control and $ESUB=0.3$

ESUB.OPA

Fig. B2: Carbon tax response when reducing the elasticity of substitution. Shifts in the demand function due to a lower elasticity of substitution, need higher taxes i.e., $T_2 \geq T_1$, to stabilize emissions. Simultaneously, the model reduces GDP and increases energy use.

8.1.3 High conservation potential

Base case vs a higher conservation potential in R1

marginal cost of residential heat demand \$/GJ

	1990	2020	1990	2020
Unconstr.	9.8	12.1	9.8	12.1
-20% CO ₂	9.1	16.6	9.7	14.3

demand for residential heat

	1990	2020	1990	2020
Unconstr.	4.5	8.	4.5	8.0
-20% CO ₂	4.5	6.4	4.5	6.9

GDP in Trillion dollars

	1990	2020	1990	2020
Unconstr.	3.542	7.081	3.542	7.081
-20% CO ₂	3.542	6.822	3.542	6.832

marginal cost C-tax dollar/ton C

2020	2020
327	314.1

A new technology is introduced in the space heating sector R1 which conserves energy at high cost, a kind of "backstop" technology for carbon taxes in the end-use markets. The cost of conservation for R1 was defined such that it becomes economic only under the CO₂ constraint. Thus, the unconstrained cases are the same. Now, in the constrained cases the marginal cost of R1 decreases due to the new conservation technology, the demand increases due to the reduced marginal cost of R1 and finally, GDP increases because a cost effective technology is introduced. This behavior explains the ability of MM to capture feed-backs between the energy system, demand variation and economic implications in an integrated framework. It takes sometime to understand the model results but then you admit that this behavior is reasonable.

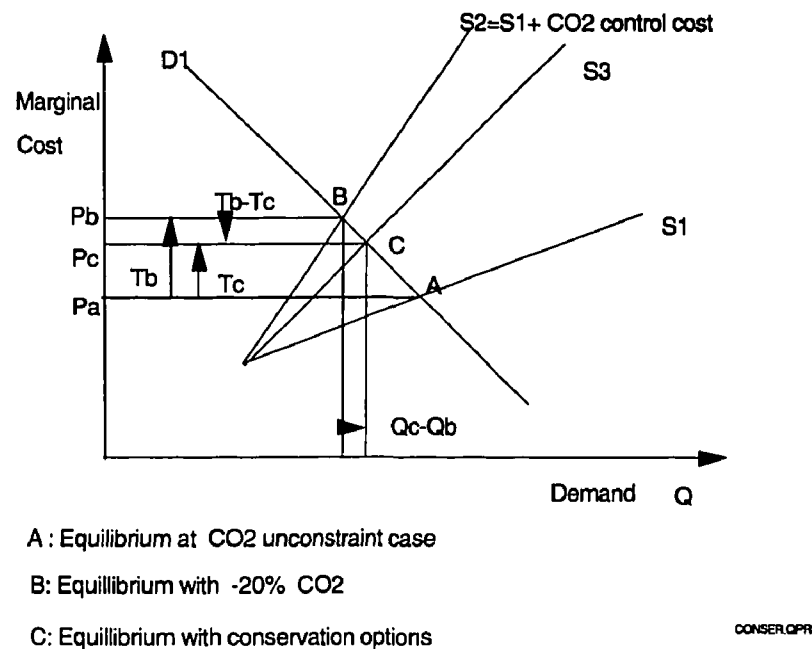


Fig. B3: Changes in equilibrium demand under CO₂ control and conservation options. Efficient conservation options reduce taxes, increase energy service and the economic output.

The figure explains how a new conservation option changes the equilibrium point under the CO₂ constraint. The first supply curve (S1) corresponds to the results obtained in the base case. The second supply curve (S2) corresponds to the supply cost of CO₂ control. The S3 curve includes conservation options (HCON case). The introduction of the CO₂ constraint in the reference case increases the marginal costs of supply from 12.1 \$/GJ to 16.6 \$/GJ. This is either due to the need to substitute for fossil fuels that generate electricity or to use new and expensive end-use devices. The high marginal cost reduces demand in a significant way. Now, introducing a conservation technology we can satisfy demand at lower cost. Thus, the marginal cost is reduced to \$ 14.3 /GJ. Simultaneously demand goes to 6.9 from 6.4 Exajoules, (the Rebound effect).

8.2 Conclusions on sensitivity

Changes in the demand and supply function of the model have been introduced and the model behavior is illustrated. The sensitivity analysis done explains how the modified coefficients of the model (AEEI and ESUB) influence the results and the estimated carbon tax. The conservation options explicitly introduced in MARKAL-MACRO define a new supply curve with significant changes in the equilibrium point between demand and supply and reduces the carbon tax. Therefore, it is of primary importance to properly define the model coefficients and the options for conservation.

9 Appendix C; Partial equilibrium

9.1 Introduction

Environmental policy introduces severe constraints in the energy systems of a country. There is a need for consistent calculations that properly represent and capture the feed-backs between energy demand and supply and between the energy system and the overall economy. This Annex formulates an algorithm as a non-linear optimization problem (NLP) that establishes partial equilibrium between energy demand and supply and clears the energy markets.

Econometric simulation models project energy demand as function of economic activity, fuel prices, technical innovation and policy actions. Linking this econometric models with engineering bottom-up models via an endogenous specification of the energy intensities we can estimate demands for energy services as function of prices, income and other exogenous variables.

Finally, linking the demand projections with an energy supply model we can merge together models based on a technological representation of the energy system with models describing the consumer's behavior and define the equilibrium fuel prices in the energy markets. The algorithm solves for equi-

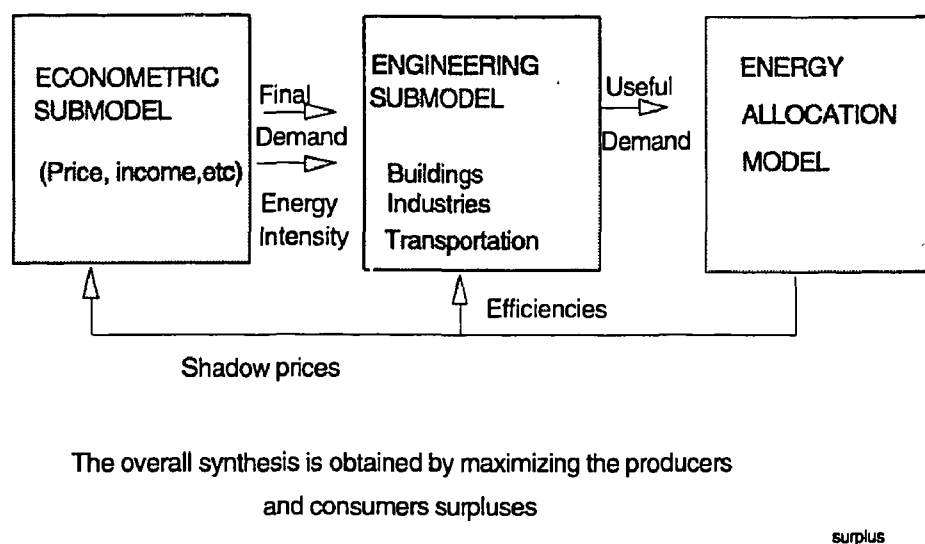


Fig. C1: The flow of information across the submodels

librium using optimization methods and guaranties consistency between the different submodels. Figure C1 gives an overview of the proposed link.¹⁷

¹⁷Prof. R. Loulou (1994) has re-initiated the issue in 1994, presenting a linearized version of the algorithm for partial equilibrium based on PIES. Afterwards and independent of my proposal, Denise Van Regemorter of the Center for Economic Studies KU Leuven, Belgium, developed the partial equilibrium approach similar to the one proposed in this report and introduced the programming changes in MARKAL.

9.2 The PIES algorithm

The PIES¹⁸ algorithm defines the partial equilibrium between energy demand and energy supply as an optimization problem. The basic idea is that the equilibrium point (P_e, Q_e) which is defined as the interception of the demand and supply curve can also be defined as the point that maximizes the producers and consumers surpluses. The following Figure explains this idea in an intuitive way. The surface S_A (the integral below the demand curve) minus the surface S_B (the integral below the supply curve) gets its maximum when the variable Q (starting from Q_a) becomes Q_e . This is equivalent to the statement:

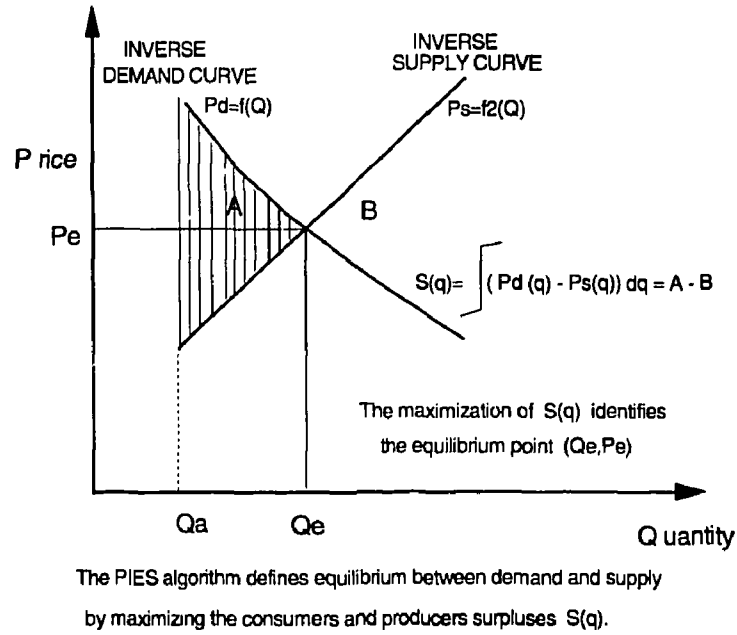


Fig. C2: The PIES algorithm

$$\text{Max } Z(Q) = \int_{Q_a}^Q P_d(q) dq - \int_{Q_a}^Q P_s(q) dq = \text{Max } (S_A - S_B) = Z(Q_e) \quad (79)$$

$P_d(q)$ and $P_s(q)$ are the inverse demand and supply functions. Obviously, differentiating relative to quantity q , and applying the maximization condition we get $P_d = P_s = P_e$.

It follows an example that demonstrates the relation given above when the demand and supply functions are analytically defined. Assuming that energy demand increases with income Y and decreases with price P , and that α and σ are the income and price elasticities of demand, the function can be written as:

$$Q_d = Y^\alpha * P_d^{-\sigma} \quad (80)$$

¹⁸The first publication that refers to this algorithm is due to W. W. Hogan from the year 1975 and discusses the partial equilibrium in the level of final energy use.

The supply function is assumed to be an increasing function with price.

$$Q_s = aP_s^\gamma \quad (81)$$

The inverse demand and supply functions are:

$$\begin{aligned} P_d &= (Q_d/Y^\alpha)^{-1/\sigma} \\ P_s &= (Q_s/a)^{1/\gamma} \end{aligned}$$

In such a representation of the energy markets the equilibrium point is defined as the point where $P_d = P_s = P_e$. This equation defines the equilibrium demand as:

$$Q_e = \frac{Y^{\alpha\gamma/(\sigma+\gamma)}}{a^{\sigma/(\sigma+\gamma)}} \quad (82)$$

Usually complex energy systems and the supply cost functions are described with the help of a linear programming (LP) model like MARKAL. In such a case we can easily extend MARKAL and formulate the partial equilibrium problem making the following observations:

- The surface below the supply function P_s , given for a demand category and a time step, corresponds to the objective function Z of MARKAL which is called PRICE. The objective function Z is the discounted system cost over all time periods that satisfies a prespecified set of energy services or demands.
The marginal cost per demand category equals to the increase in the system cost per unit increase of demand. Thus, the marginal cost per unit of demand (price) integrated over the corresponding range of demand (quantity) defines the surface below the supply curve.

If $P_q = \partial Z / \partial q$ is the shadow price of demand,
the surface below supply is: $\sum_i \int P_{q_i} dq = \sum_i \int_{q_i} \frac{\partial Z}{\partial q_i} dq_i = \Delta Z$ (Δ objective function)

$$(83)$$

- The demand function can either be an explicit analytical function to be integrated directly, or a linearization of the demand function is necessary (see R. Loulou 1994).

Therefore, the partial equilibrium problem can be defined, using the standard abbreviations of the MARKAL model, as follows:

$$\begin{aligned} \text{Max } Z(q) &= \int_{q_a}^q P_d(q) dq - \int_{q_a}^q P_s(q) dq = \int_{q_a}^q P_d(q) dq - \sum_j c_j * x_j(q) + \sum_j c_j * x_j(q_a) \\ \text{s.t.} \\ Bx - q &= 0 \quad q \text{ is the vector of demand variables} \\ Ax &\geq b \quad \text{the usual MARKAL constraints} \end{aligned} \quad (84)$$

If the demand function is the one given above i.e., $D/D_0 = (P/P_0)^{-\sigma}$ then the surface below the demand curve is defined directly by integration, for $\sigma = 1/(1 - \rho)$ we have:

$$S(q) = \frac{P_a}{\rho Q_a^{\rho-1}} * (q^\rho - q_a^\rho) \quad (85)$$

and the NLP problem solving for partial equilibrium can be formulated as follows (excluding the constant terms):

$$\begin{aligned} \text{Max } Z(q) &= \text{nyrs} * \sum_i \frac{P_{i,a}}{\rho_i Q_a^{\rho_i-1}} * q_i^{\rho_i} - \sum_j c_j * x_j \\ &\text{s.t.} \\ Br - q &= 0 \\ Ax &\geq b \end{aligned} \quad (86)$$

The *nyrs* represents the years per period while the shadow prices $P_{i,a}$ are given in discounted values. In other words, the old objective function Z , of MARKAL called "PRICE" has to be changed to a new function called "SURPLUS" defined as the integral of the demand function minus the old "PRICE" function. The demands q_i become now variables in the GAMS formulation.

Thus, the procedure for solving the partial equilibrium problem could be as follows:

- Define first a set of demands for energy services in MARKAL, solve the inelastic MARKAL problem e.g., with fixed demands, and specify the first equilibrium point $(P_{0,\epsilon}, Q_{0,\epsilon})$ for each time period and demand category.
- Then, assuming as starting point of integration, $Q_a = 1/2 * Q_{0,\epsilon}$ i.e., the half of the value estimated in the first MARKAL solution, and $P_a = P_{0,\epsilon}(1/2)^{-\sigma}$, integrate and solve for partial equilibrium using the new objective function "SURPLUS".

This procedure will satisfy the maximization condition for the consumers and producers surpluses and it will solve for partial equilibrium.

The advantages of using a partial equilibrium MARKAL, relative to the MARKAL-MACRO model is that the model user will be able to define different price and income elasticities per sector and energy services.

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