Modelling Regional Energy Consumption and CO₂ Emissions: An Information and Scenario Tool for Practitioners

Gregor Dürrenberger¹ and Christoph Hartmann²

Zusammenfassung

Der vorliegende Artikel beschreibt den methodischen Ansatz, die Datenbasis und die Unsicherheiten eines Modellierungsinstruments, das den regionalen Energieverbrauch und die damit verknüpften CO₂-Emissionen zu berechnen, sowie mögliche Entwicklungen bis ins Jahr 2030 abzuschätzen erlaubt. Das Modell ist auf schweizerische Verhältnisse kalibriert und auf eine Benützung durch regionale Entscheidungsträger zugeschnitten.

1. Introduction

Many pressing environmental problems like air pollution, climate change, acid rain, and deforestation – to name but a few – are directly linked with energy consumption. In order to mitigate these problems, energy demand needs to be substantially reduced. An important step towards such a goal is the Climate Convention in which western countries commit themselves to CO₂ emission reductions. Switzerland, for instance, needs to reduce output from 45 million tons per year at present to 41 million tons by 2012.

Such a decrease in CO₂ emissions requires substantial savings in the consumption of fossil fuels. In order to define effective saving-strategies, decision-makers need solid information about reduction potentials and the effects of demographic, economic and technological developments on long-term energy demand. In general, such information is available for national levels only. Local policy-makers can barely back their strategic decisions with regional data. This lack of data is....

¹ Laboratory for Electromagnetic Fields and Microwave Electronics, Swiss Federal Institute of Technology, ETH-Zentrum, 8092 Zurich.
email: Gregor@ifh.ee.ethz.ch, Internet: http://www.ifh.ee.ethz.ch/~gregor

² Amstein + Walthert AG, Leutschenbachstr. 45, 8050 Zurich.
email: christoph.hartmann@amstein-walthert.ch, Internet: http://www.amstein-walthert.ch
problematic because, in the context of Local Agenda 21 processes, regional initiatives have substantially grown in both number and importance in recent years. In this paper, we will present a computer-modelling tool for local decision-makers which allows the calculation of regional energy and CO₂ budgets and makes energy and emissions projections. The model has been developed in the context of a research project funded by the Union of Swiss Cities, the Swiss Environmental Protection Agency and the Swiss Federal Institute of Technology. The final tool will be available by the end of 2001, approximately.

2. **Systems Description**

2.1 **Intention and Approach**

The intention of our modelling project was to design a user-friendly computer tool which meets the following demands: it budgets regional energy requirements and associated CO₂ emissions; accounting is flexible with regard to spatial scales; the model differentiates between net and gross consumption; it calculates balances for both direct and embodied energy; it allows for scenario building; and finally, the tool can be handled by practitioners without time consuming training.

Officials in public administrations were defined as core-users of the model by the project. However, the tool will also be made available to other practitioners. Possible addressees are representatives from NGOs, teachers, and interested people from the scientific community and from the general public.

The modelling work is based on material flow analysis (Baccini/Bader 1996). In this approach, systems and models are described by flows and processes. For our purposes, the relevant flows are defined as energy flows, and the relevant processes as those associated with energy production and consumption. We built a baseline model, which represents Switzerland, and a baseline scenario (2000-2030), which embodies Swiss trends. Regional budgets and trends are constructed by downscaling, i.e. parameter variation. The project could strongly benefit from previous modelling work (Schlumpf/Behringer/Dürrberger/Pahl-Wostl 1999, Dürrberger/Patzel/Hartmann 2001).

Concerning energy flows, the model discriminates between direct energy flows associated with the consumption of energy carriers (including electricity) and embodied energy flows related to goods and services consumption. The embodied energy of a commodity is defined as the fossil energy required for producing the commodity.

With regard to processes, the model differentiates between domestic energy production, energy distribution, goods and services production, and household demand. The two main processes (goods and services production, household consumption) are divided into sub-processes in order to allow detailed modelling.
CO₂ emissions are derived from the flows of energy carriers (for direct emissions) and from the flows of commodities (for embodied emissions). The model uses separate emission factors for the energy carriers. For emissions embodied in imported commodities, a mean emission factor, which reflects the production conditions of the main Swiss trading partners, is applied.

2.2 Selected Elements

2.2.1 Direct Energy Flows

The model differentiates between 10 energy carriers (oil, gasoline, diesel, kerosene, gas, coal, electricity, firewood, waste, distant heat) and between end- and gross-energy. Gross energy-flows, which include pre-combustion, are calculated on the basis of non-renewable energy requirements. All flows are separated into import, export and internal flows.

Fossil fuels and uranium are imported and consumed by the system. After consumption, direct energy is exported as heat. Gross electricity imports are calculated with the European production mix (UCPTE), gross exports with the domestic production mix (Frischknecht et al. 1996, Habersatter et al. 1996).

Internally, direct energy flows from the process “energy distribution” to the processes (and sub-processes of) “goods and services production” and “household consumption”. The process “domestic energy production” delivers direct energy (electricity, heat from firewood, heat from waste incineration, and distant heat) to the process “energy distribution”, and households supply domestic energy production with waste for incineration.

All data for modelling direct energy flows stems from official Swiss sources. For the status quo description data was selected from the National Energy Statistics, reference year 1995 (BfS, 1996a).

2.2.2 Embodied Energy Flows

All fossil energy used for the production of commodities is allocated to these commodities. It is called embodied energy. With regard to imports and exports, the model discriminates between 29 baskets of commodities. For each basket, embodied energy is calculated with the help of trade statistics, domestic energy statistics and LCA-data. For calculating export values, all non-renewable energy used by the domestic economy for the production and/or upgrading of export-products is allocated to these products.

With regard to household demand, the model operates with 20 commodity baskets. 9 baskets relate to goods, 11 baskets concern services. All net-energy (direct as well as embodied) consumed by the industry is allocated to the commodity
baskets of household demand. Allocation is made top-down and takes into account cross-sector exchange (see below).

Data stems from two sources: LCA data, including data for the energy carriers, is taken from the database eco™ of ESU-services – a leading Swiss consultant for lifecycle assessment. Trade data stems from official Swiss trade statistics (BfS 1994, 1996b). In order to minimize economic fluctuations, the model uses mean values of the years 1994 and 1996 instead of the 1995 data only.

2.2.3 Economy

The process “production of goods and services” consists of 28 sub-processes (economic sectors). Each sub-process consumes direct, as well as embodied, energy. Direct energy is supplied by the process “energy distribution”, embodied energy stems from imports and/or other sub-processes. Output-flows consist of embodied energy only (exports and deliveries to other sectors and households). Cross-sector trade is modelled with 6 different exchange patterns. Exchange rates are based on employment data.

Net-energy consumption of the sub-processes is allocated to commodity baskets of household consumption (see below). Retailing enters into most of these baskets. If no data (sector output by products) for allocation was available, economic insiders were asked for their expert judgment.

2.2.4 Households

The process “household consumption” demands direct energy from the process “energy distribution” and embodied energy from the process “production of goods and services”. Output flows are heat and energy embodied in waste. Part of the embodied energy feeds back into domestic energy production (waste incineration).

Direct energy is differentiated into 6 domestic energy services (e.g. heating, warm water, cooling, etc.) and 3 mobility services (private mobility, public transportation, air mileages). Embodied energy is grouped into 20 commodity baskets (e.g. food, furniture, clothing, building, health care, education, holidays, etc.).

Sub-processes are defined by household size (6), income (5 levels), car (2) and house ownership (2). Delineation is based on statistical data and, if no data was available, on conservative guesses. The latter was mostly the case for income related discriminations.

2.2.5 Stocks

The model does not account for stocks. All stocks are handled as flows. The building stock is modelled as average annual energy flow from the building sector into other economic sectors (commercial buildings) and into households (residential
buildings). Economic growth of the building industry is set at mid 90’s mean value. The same proceeding is applied to other stocks of infrastructure.

2.3 Variables and Parameters

2.3.1 Variables

All energy and CO2 flows are variables. Import-flows of direct and embodied energy are calculated with the help of 3 parameters: quantity (in kg), production energy (in MJ/kg, fossil component only), and calorific value (MJ/kg). Export flows and internal flows are calculated with linear equations.

The model handles 344 output variables. These variables are grouped into 5 topical and 8 accounting categories. Users simply choose a topic and an accounting category and the model selects and calculates the relevant variable sub-set. All results are presented graphically.

An accounting category is defined with three choices. One decides, first, whether the model should calculate regional gross- or net-consumption, second, whether energy use or CO2 emissions should be budgeted, and third, whether the model should compute gross-energy or end-energy requirements.

Topical categories relate to subsets of thematically grouped variables. The following subsets are defined: energy carriers (10 variables: see 2.2.1); mobility (8 variables: private mobility and freight traffic differentiated into the modes road, rail and air; business traffic differentiated into road and air); domestic consumption (5 variables: consumption of heating, mobility, other energy services, goods, and services); consumption of economic sectors (12 variables, each representing a sector); overview of regional consumption (8 variables: agriculture, industry, service sector, private mobility, business traffic, freight traffic, household consumption differentiated into direct and embodied flows).

2.3.2 Parameters

The parameters for calculating imports have been mentioned above. Parameters for modelling cross-sector flows within the economic process are defined on the basis of exchange patterns and sector employment. Parameters for calculating flows from the economic sectors to the households are derived from economic statistics. In cases where no data were available parameters were defined with the help of economic experts.

Parameters for constructing scenarios will be listed in section 3.2.
3. Regional Modelling and Scenario Building

3.1 Regional Downscaling

The model calculates regional budgets and scenarios by scaling down Swiss data to local conditions. The parameter set used for downscaling consists of 34 items: population (1 parameter), household structure (5 parameters), and employment (28 parameters). For downscaling, regional technology (production conditions) and regional lifestyles (consumption patterns) are set constant at the Swiss average.

In order to obtain valid regional data, the size of a region should not be below approx. 200'000 inhabitants. Cantons or larger Swiss agglomerations meet this criterion.

For calculating a regional budget, users have to feed the model with regional data for population, household structure and employment. In general, this data is easily available. In contrast to that, most output data computed by the model cannot be found in regional statistics.

3.2 Scenario Building

3.2.1 Trend Scenarios

The model uses Swiss trend data for constructing regional scenarios. For trend calculations, the same downscaling approach is applied as for status quo budgeting. All trend data is taken from a prognostic study published by the Swiss Energy Office (BfE 1996). The model uses time-series for both variables (direct energy flows broken down into energy carriers) and parameters (population, household structure, employment).

On the basis of the regional status quo data (population, household structure, employment) the model calculates a trend scenario (2000-2030). It is assumed that regional demographic and employment trends, technological dynamics and local consumption behaviour follow Swiss trends.

However, users can vary these assumptions and construct scenarios with parameter values that differ from the trend settings.

3.2.2 User-Defined Scenarios

For individual scenario building, users can modify all demographic and economic parameters. In addition, they can change the following 10 parameters which drive technical progress and consumption trends: Energy efficiency of the production sector, the domestic sector, private mobility, and freight traffic; growth rates of private mobility, freight traffic, and household demand; modal split of private mobility and freight traffic; production mix of electricity.
To set these parameters at individual levels one can choose values from pre-defined drop-down lists. Default setting of the parameters is always “trend”.

Scenarios can be run for all output variables. Results are presented graphically. The interface concurrently displays the data of the trend scenario and of two user-defined projections. This allows for comparisons and stimulates additional scenario building.

5. Uncertainty

5.1 Model Validation

A full-scale model validation cannot yet be presented. However, first results are encouraging. In this section, we will focus on the baseline model, i.e. Switzerland, on overall consumption, and on household consumption.

In our model, net-consumption of gross-energy (direct and embodied energy) amounts to 1540 PJ for 1995. According to Knoepfel (1995) and Zaccheddu (1997), that used input/output data, Switzerland consumed 1260 PJ in 1990. According to a study that followed a similar approach as applied in our work (Biedermann/Hofstetter/Schläpfer 1992), consumption summed up to 1400 PJ in 1991. Adjusted to the reference year 1995, the difference between these studies and ours is around 7%.

With regard to CO₂ emissions, validity of our results is in the same order of magnitude. In a recent study (Frischknecht/Jungbluth 2000) that used a process-chain approach, the overall per capita net-emission was calculated at 11 tons in 1998, which is very close to our 10 tons for 1995. According to the Swiss greenhouse gas inventory, gross-emissions of CO₂ stemming from (direct) energy consumption amounted to 43.8 Mio. tons in 1995. Our model calculates 40.7 Mio. tons. The difference is approx. 7%.

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Model</th>
<th>I/O-Table</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food</td>
<td>15.4</td>
<td>16.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Clothes</td>
<td>3.8</td>
<td>4.4</td>
<td>17.2</td>
</tr>
<tr>
<td>Housing</td>
<td>19.1</td>
<td>17.8</td>
<td>-6.9</td>
</tr>
<tr>
<td>Furniture</td>
<td>7.0</td>
<td>6.1</td>
<td>-13.1</td>
</tr>
<tr>
<td>Health</td>
<td>10.0</td>
<td>11.1</td>
<td>-10.8</td>
</tr>
<tr>
<td>Mobility</td>
<td>18.7</td>
<td>19.5</td>
<td>8.7</td>
</tr>
<tr>
<td>Leisure</td>
<td>7.3</td>
<td>19.1</td>
<td>11.8</td>
</tr>
<tr>
<td>Misc.</td>
<td>18.7</td>
<td>16.3</td>
<td>-12.8</td>
</tr>
</tbody>
</table>

Table 1

Distribution of household energy consumption by commodity categories, in %. First data row: model results, second data row: results from input/output analysis, third data row: difference between the two approaches

With regard to household consumption, we compared our results for embodied energy with corresponding data from an input/output analysis. We limit discussion...
to a comparison of the energy distribution into commodity baskets. Such limitation is acceptable because overall energy consumption is almost equal in both approaches.

The input/output analysis for this comparison was done by ESU-services. The main results are presented in table 1. There is a surprising match between the results of our model and the data derived from the input/output table.

Findings from a detailed process-chain analysis of the food sector (Jungbluth 2000) further validate our model data: According to Jungbluth annual per capita energy requirements for food amount to 21 GJ, our model computes 24 GJ.

5.2 Estimation of Uncertainties

In this section, uncertainties will be roughly assessed. Due to the model structure, uncertainty propagates linearly. For direct energy flows, uncertainty is approx. 10%, for embodied energy imports approx. 20-30%. Consequently, uncertainty of embodied energy demanded by households accumulates to roughly 15%, which is the order of magnitude observed for the commodity basket “food”. Small baskets are more uncertain than larger ones (see table 1). For tiny baskets, uncertainties will amount to 30% or more.

Data with regard to household types are less reliable than aggregated data about the household sector at large. Uncertainty is set to 20%. As a result, uncertainty for commodity consumption by household types amounts to 25-30% in case of goods and services, to 20-25% in case of energy services.

With regard to CO2 emissions, uncertainties are in the same order of magnitude as the respective energy flows. The physically and technically defined emission factors do not add significant new uncertainty.

6. Outlook

The next steps will be devoted to regional calibration. Data of selected Swiss regions will be integrated into the model. If necessary, the model will be adjusted to regional specificities, possibly by using a typology along the dimension urban - rural.

An important part of the work ahead will concern usability tests with practitioners. A small group of public officials will comment on model features and on the interface. These comments will be used to tune the model to the needs of the users.

In the course of this testing, the feasibility to integrate monetary parameters and pre-defined policy measures will be evaluated.

Finally, the model – currently running on Excel 9.0 – will be implemented on the Internet. The Internet version should be available by the end of 2001.
Bibliography