Exploring the fuel cell car future: an integrated energy model at the city level

P. Caratti[1], A. Haurie[2], D. Pinelli[1], D.S. Zachary[2]
[1] *Fondazione Eni Enrico Mattei, Italy.*
[2] *LOGILAB/HEC, University of Geneva, Switzerland.*

Abstract

This paper explores the possible penetration of fuel cell car technologies in a context of sustainable urban transportation. The analysis is performed via an integrated energy model that places all technologies and energy forms in competition for satisfying a given set of useful demands or energy services. The time horizon is 45 years. Emissions of different air pollutants are recorded and globally constrained. The model is implemented in a case study corresponding to the canton of Geneva in Switzerland. An interesting feature of fuel cell cars is their potential contribution to the production of electricity to be distributed on the grid. This feature is represented in the integrated energy model. The analysis shows when this possible integration makes the fuel cell car technology more competitive.

1 Introduction

Fuel cell units are producing electricity through a chemical process involving zero or very little emission of air pollutants. These technologies may use a variety of fuels, natural gas, methanol or hydrogen. When the fuel is hydrogen produced from nuclear or renewable energy forms this technology does not contribute to GHG emissions either. Fuel cell units can be installed in cars, the electricity being used to power electric motors that drive the vehicle wheels. An interesting features of these cars is that, when they are idle for transport usage, they could be hooked to the grid network and produce electricity for the household or the community. There is therefore a possibility to envision in the future a complementary electricity production system, using the many power units that could be also used to transport people.

The aim of this paper is to provide a first evaluation of the conditions under which such a technology could penetrate the private transportation market in urban European regions. This evaluation is made for the canton of Geneva in Switzerland, which represents a population of 425'000 people, living mostly in densely urbanised districts, with a large number of cars (approximately 200'000 cars are registered). Indeed, as the transport technology can now be involved in the production of power to be distributed on the grid, the assessment of this option must be integrated so as to take into account all the different possible ways of organising the energy system of the region. Planning of this nature is apropos for satisfaction of sustainable energy systems implemented for urban development such as the Agenda 21. A tool has been developed for that purpose. It is a system analysis model, called MARKAL-Lite [2,3], which uses an optimisation technique to assess the efficiency of an ensemble of technologies that compete for supplying the energy needed by the economy of a given region.

In what follows Section 2 describes the main features of Markal-Lite (for a full description of the model see [2,3]). Section 3 discusses the assumptions concerning the parameters that define the long-term socio-economic scenarios that drive the simulations performed by the model (including the environmental constraints to be imposed). Section 4 lists the technologies in competition. Section 5 describes the economic and environmental characteristics of fuel cells. Section 6 discusses the results. Section 7 summarises the conclusions.

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2 The MARKAL-Lite model

MARKAL-Lite is an energy model, describing the possible systemic choices in the organisation of the energy system available at the city level. It derives from MARKAL [4] and takes its name from the reduced scope of the energy system that is represented. MARKAL-Lite considers the transportation system as a part of the larger energy production and consumption system in an urban region. This holistic approach is justified by the development of combined technologies, like the power/heat co-generation plants that can be used to heat buildings and contribute to the production of electricity, or the fuel cell cars that can be used to produce electricity when they are idle. In what below, we only summarise the main features of the model. A full description of the model is in [2,3].

Figure 1 shows the fundamental organisation of the so-called energy reference system (RES). The whole model is driven by the useful demands, or energy services, forming the class DM. In order to provide the services one has to install and use demand device technologies forming the class DMD; these technologies use final energy forms that are produced either by process technologies forming the class PRC, when the energy form is storable, or by conversion technologies forming the class CON, when the energy is non-storable (as it is the case for electricity and low temperature heat); these energy transformation technologies use *primary energy forms* that come from the *energy* *sources,* forming the class SRC. The arrows in this diagram represent flows of energy carriers.

MARKAL-Lite therefore represents an energy system composed of a set of technologies transforming and trading energy forms in order to satisfy the set of exogenously defined *useful demands*. As in MARKAL the energy production technologies are associated with three activities, representing *capacity, investment, operation*, respectively. These technologies will exchange *energy flows* and generate *pollutant emissions*. Also, as in the original MARKAL model, the demand technologies are represented through two activities only, *capacity* and *investment*, assuming that the average operation level is fixed, once such a technology is installed. Two points are worthwhile to remark. Firstly, a technology

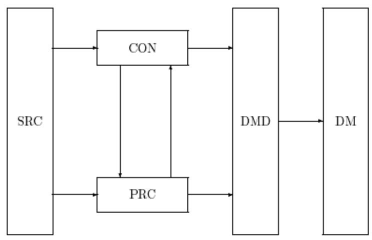

Figure 1: MARKAL RES

is a resource transformer also contributing to emission of pollutants when it operates. This is one on the main process to be represented in the model. Secondly, the operations levels are upper-bounded by the installed capacity. The capacity is transferred from one period to the next and increased through the investment process. This describes the dynamics (i.e. the capacity expansion process) of the production system.

MARKAL-Lite, like the original MARKAL is basically a capacity expansion model for a multi-technology production system. The model puts into competition a large array of potential technologies and energy forms with possible cascading effects (i.e. co-generation or power/heat coupled production). The representation of the investment and capacity transfer processes, makes the model appropriate for analysing policies in a transition from one context, e.g. the low cost unlimited oil supply, to a very different one, like the sustainable development scenarios envisioned by modern cities.

3 Scenario parameters

In this section we propose values for the parameters that define the long-term socio-economic scenarios that will drive the simulations performed by the model.

3.1 Useful demands

The energy system is driven by the so-called useful demands that describe the different energy services that will be in demand due to the demography and economic activity of the region into consideration. Table 1 shows the useful demand for heat and captive electricity usage projected to 2035. They are expressed in PJ/year (1 PJ=1015 J), for a succession of nine 5-year periods, starting in year 1990 and finishing in year 2035.

Table 1: Demand for heat and captive electricity usage (PJ/year)

	Period Sector	1	2	3	4	5	6	7	8	9
I1	El. Industrial	0.54	0.58	0.63	0.67	0.72	0.76	0.81	0.85	0.85
IA	LTH Industrial Area	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
R1	El. Residential	1.62	1.67	1.69	1.72	1.76	1.8	1.84	1.87	1.87
R2	El. Commercial	3.02	3.23	3.61	4.21	4.88	5.54	6.20	6.86	6.86
R3	El. Public Use	1.03	1.11	1.19	1.27	1.36	1.44	1.52	1.60	1.60
R4	El. Public Light	0.09	0.1	0.11	0.12	0.13	0.14	0.15	0.16	0.16
RA	Heat Existing Building 2-9 appts	11.90	11.68	11.57	11.46	11.36	11.25	11.15	11.04	11.04
RB	Heat Existing Houses	1.28	1.26	1.25	1.24	1.23	1.22	1.21	1.20	1.20
RC	Heat New Buildings 2-9 appts.	0.63	1.14	1.65	2.16	2.67	3.19	3.70	4.21	4.21
RD	Heat New Houses	0.07	0.12	0.18	0.24	0.29	0.35	0.40	0.46	0.46
RE	Warm Water for Buildings	4.09	4.11	4.13	4.15	4.17	4.19	4.21	4.23	4.23
RF	Warm Water for Houses	0.34	0.35	0.36	0.38	0.39	0.40	0.42	0.43	0.43

Table 2 shows the projected *useful demand for transportation services*. They are expressed in 1'000 km/day. The trend in these demands has been obtained from demographic analysis and an assumption of continuing transportation habits.

Table 2: Demand for transport (1'000 km/day)

	Period Sector	1	2	3	4	5	6	7	8	9
TE	Automobile	4632	4684	4715	4746	4777	4808	4840	5005	5005
TL	Delivery vehicles	244	247	298	298	298	298	298	298	298
TA	Public Transports: Bus	70.27	73.57	81.87	87.67	93.47	99.27	105.07	110.87	110.89
TH	Truck	83.80	87.74	102.43	102.43	102.43	102.43	102.43	102.43	102.43
TB	Public Transports Tramway	10	17.6	34.67	36.04	37.41	38.79	40.17	41.54	41.54
TC	Public Transports: Train	7	8.25	9.38	9.75	10.12	10.49	10.86	11.23	11.23
TD	Public Transports Misc.	1	4.7	7.26	7.548	7.836	8.124	8.412	8.7	8.7

3.2 Imported energy prices

The prices of imported energy forms are the other group of important driving forces for the energy market. The following prices are constructed on the basis of prices observed on the European market in 1999 or 2000:

Fossil fuel price: Non transportation use: The figures given below reflect the pre-tax European market prices in 1999 for fuels used for non-transportation usage.

- COA; coal : EURO-3.740/GJ.
- NGI; natural gas for industry : EURO-11,828/GJ.

Fossil fuel price: transportation use In 2000 the following pre-tax prices per litre of different fuels were estimated :

- DST; diesel fuel : EURO-0.234 per litre, that is EURO-9,643/GJ.
- GSL; gasoline unleaded : EURO-0.242 per litre, that is EURO-10,676/GJ.
- GSW; gasoline with lead : EURO-0.207 per litre.
- LPG; natural gas for cars : EURO-0.327 per litre, that is EURO-20,929/GJ.

New fuels

- MET : methanol EURO-125 per ton which means EURO-8,152/GJ.
- ETH : ethanol EURO-125 per ton which means EURO-7,022/GJ.
- HDG : hydrogen EURO-10 per GJ.

In principle, as the model runs over a 45 year time horizon one needs to provide forecasts for the energy prices. Since we intend to evaluate technology choices we have decided not to introduce variations in the fuel price structure over the whole planning horizon. We avoid the thorny issue of predicting the price of oil and other fossil fuels over the next decades. The technologies are compared under the assumption that the price structure remains more or less the same. Also we did not include taxes in the energy price. Again, this is justified in an exercise where one tries to identify the technologies that could be most efficient in solving the systemic environmental problems in urban communities.

3.3 Environmental objectives

We consider three levels of environmental objectives that will translate into emission constraints in the model.

1. We assume that the policy in this urban region consists first in reducing the emissions of ozone precursors (NO_2 and VOCs principally).
2. A second possible environmental objective is to reduce the emissions of CO_2 in conformity with Kyoto/Marrakech agreements.
3. A third-level environmental objective, that is compatible with Agenda-21 (adopted by the canton of Geneva) is to reduce the dependency on "imported electricity", mostly produced from centralised technologies (dams, nuclear paints, etc.). This would increase the use of decentralised (local) production via coupled technologies.

3.3.1 Ozone indicators

Ozone pollution is related to episodes, ie weather and emission patterns that trigger concentration increases in different areas of the concerned region. One may therefore represent the O_3 pollution through the use of indicators that are built from the prevalence of these critical weather conditions over a typical year. Such indicators are for example the *peak ozone,* the *average over threshold,* and the *average population exposure.* Details on the construction of these indicators can be found in [5]. In the particular case where only the precursors due to transportation are considered, it has been found possible to represent in a single linear expression the relationship between the precursor emissions and the O_3 pollution indicators (see [5]). The relationship obtained reads as follows:

$$\text{Ozone-Peak} = 0.0157 * NO_2 + 0.00086 * VOCs, \quad (1)$$

where the ozone peak indicator is related with the yearly $AT0_2$ and VOCs emissions due to transport. In the scenarios that we study this ozone peak indicator will be constrained as follows

Table 3: Upper bounds on ozone peak indicator

	1	2	3	4	5	6	7	8	9
Ozone- Peak:	60	60	60	30	20	10	9	5	4

3.3.2 CO_2 emissions

The second environmental constraint, imposed on the energy system concerns the emissions of CO_2, the major greenhouse gas produced by the use of fossil fuels. This schedule corresponds to an objective of 90% of the 1990 emissions level reached by 2020.

Table 4: Upper bounds on global CO_2 emissions- MT/Y

	1	2	3	4	5	6	7	8	9
CO_2:	2.3	2.3	2.3	2.3	2.12	2.09	2.09	2.09	2.09

3.3.3 Reduction of electricity imports

The third environmental constraint concerns a reduction of the imports of electricity in the region considered. This question is specific to the Geneva canton where a "constitutional" law forbids the use of nuclear energy to produce electricity. As the electricity imported is at 40% of nuclear origin, the canton would reduce by a similar fraction its current imports, obtained by contract with a power supplier in Western Switzerland. This type of policy

Table 5: Upper bounds on electricity imports PJ/Y

Period:	1	2	3	4	5	6	7	8	9
PJ:	5	5	5	4	4	3.5	3.5	3	3

also finds a justification in the desire to promote decentralised power systems, avoiding the efficiency losses caused by long distance transport and environmental damages caused by centralised production units (dams, nuclear plants, coal power plants).

4 A list of technologies in competition

The model simulates a market where different technologies compete for the production of energy forms and energy services that are demanded.. In particular, the model includes the following types of cars.

Table 6: Types of Cars

TE1	Automobile Diesel	TEN	Automobile natural gas (LPG)
TE2	Automobile, Catal.	TES	Automobile electric small/medium
TE3	Automobile gasoline w. Lead	T1Q	Automobile Fuel Cell Hydrogen
TE4	Automobile Diesel French	T1R	Automobile Fuel Cell Methanol
TE5	Automobile gasoline French	T1S	Automobile Fuel Cell Gasoline
TE6	Automobile gasoline w/lead French	TIT	Automobile Fuel Cell Natural Gas

5 Fuel cell cars: a techno-economic description

We distinguish two broad categories of FCCs: (i) those powered by hydrogen provided by an independent network and (ii) those producing hydrogen on board, using a fossil fuel. The first category includes 1 technology (T1Q), the second category includes 3 technologies (T1R, T1S, TIT) using, methanol, gasoline and natural gas respectively.

The fuel cell unit is characterised by two different efficiencies depending on its final use, either as a transportation device or as a power generator.

5.1 Cost

Capacity unit for cars is expressed in 1'000-km/day. The investment costs are estimated at 1.37 E+6 EURO to 2 E+6 EURO.

Yearly maintenance cost are estimated to be 1/30 of the investment cost, giving a range of EURO 0.046 to EURO 0.067.

Methanol and natural gas powered FCCs will not need a new development of service stations. For hydrogen powered FCC specific distribution costs should be added.

5.2 Emissions rates

The emission rates for FCCs are exceptionally low. A typical FCC, the Necar 3, is powered by hydrocarbon fuel. The emission rates are 0 for *CO,* 0 for NO_X, 0 for particulates, 123 g/km of CO_2, 0.005 g/km of VOCs (HC). The hydrogen FCC has 0 emissions rates for all pollutant types. Converting these figures in terms of capacity units corresponding to 1'000-km/day, that is 300'OOQ km/year we obtain emission rates of, 36.9 tons of CO_2 and 1.5 tons of VOCs per year per unit of capacity.

6 Simulation results

This section presents numerical results of simulations using the MARKAL-Lite model for Geneva, Switzerland. There are two main scenarios. In the first scenario, we consider only local abatement measures. In the second scenarios, we also impose additional constraints on electricity imports. For each scenario, two sets of results are produced: the penetration of FCC in the car market, and the penetration of FCC electrical production in the electricity market. All results are shown for all the 45 year time horizon.

Fig. 2 & 3 show FCC car penetration for the *local abatement scenario*. Fig. 2 shows that, when constraints are imposed, all non-FCC cars disappear with the exception of the catalytic converter car (TE2) which remains with a total capacity of 1800 demand units.

Fig. 4 & 5 show FCC car penetration for the *additional constraints on electricity imports* scenario. In this case we note a stronger and earlier penetration of fuel cell cars with respect to the *local abatement scenario* (Fig. 3). The total use of FCCs reaches 3200 demand units. The incremental cost w.r.t. the scenario 1 of both the CO_2 constraint and electricity imports bounding is 1038 M$ (discounted cost increase over the 45 year period).

Fig. 6 shows the onset of electricity production from FCCs (with and without constraints on imports). A tripling of output is seen in the later period when import constraints are imposed (O_3 and CO_2 abatement does not play a major role in electricity production.). Electricity production penetrates the market in the year 2010 and reaches peak production values of 2.5 (M Euro/Yr) in the year 2030.

FCC Capacity : Full Abatement, No constraints on Imports

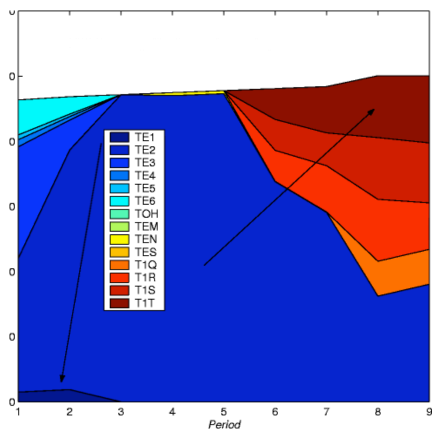

Figure 2: Fleet composition: the capacity (units of 1000 km/day) per period for fuel cell cars and standard automobiles under the conditions of *full abatement* and *no constraints* on imports.

FCC Capacity : No Abatement, No constraints on Imports

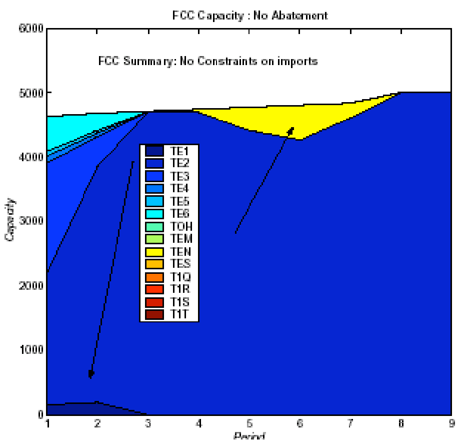

Figure 3: Fleet composition: the capacity (units of 1000 km/day) per period for fuel cell cars and standard automobiles under the conditions of *no abatement* and *no constraints* on imports.

FCC Capacity : Full Abatement, constraints on Imports

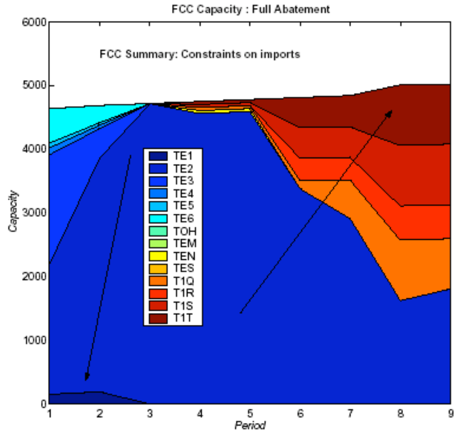

Figure 4: Fleet composition : the capacity (units of 1000 km/day) per period for fuel cell cars and standard automobiles under the conditions *of full abatement* and *constraints* on imports.

FCC Capacity : No Abatement, constraints on Imports

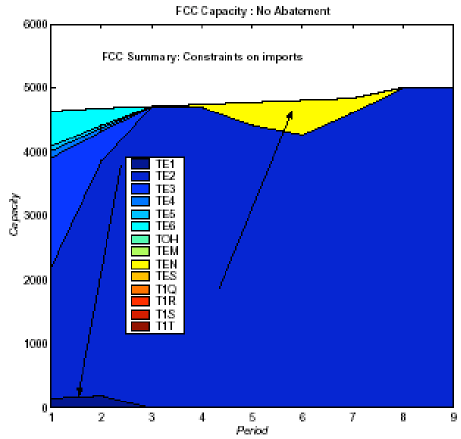

Figure 5: Fleet composition : the capacity (units of 1'000 km/day) per period for fuel cell cars and standard automobiles under the conditions of *no abatement* and *constraints* on imports.

Elec. Output (MEuro/YR)

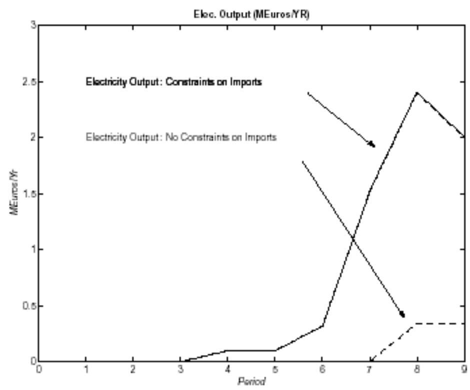

Figure 6: Electric Output for FCC showing the comparison with and without import constraints. Only the hydrogen fuel cell cars contribute to electricity production.

7 Conclusion

Fuel cell cars scenarios have been implemented into the MARKAL-Lite model for Geneva, Switzerland with a time horizon of 45 years. This new technology shows economic feasibility and therefore penetration into the market at the year 2010 or 2015 (depending on abatement strategy). The impact into the market is strongly dependent on environmental abatement strategy and in fact, no fuel cell cars penetrate the market with the absence of environmental consideration and very large penetration (approximately 60%) in the year 2035 when full CO2 and O3 abatement strategies are considered. Furthermore, the fuel cell car's potential to supply electricity to the grid has also been demonstrated. Electricity production penetrates the market in the year 2010 and reaches peak production values of 2.5 (M Euro/Yr) in the year 2030. The electricity output is highly dependent on the constraints of electricity imports. The MARKAL-Lite description for Geneva along with reasonable environmental abatement strategies show that fuel cell cars will play a very important role in fleet composition and in electrical production in the decades to come.

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