Agent based modelling and energy planning – Utilization of MATSim for transport energy demand modelling

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The transportation sector is one of the major energy consumers in most energy systems and a large portion of the energy demand is linked to road transport and personal vehicles. It accounted for 32.8% of the final energy consumption of Croatia in 2011 making it the second most energy demanding sector. Because of their higher efficiency, a modal switch from conventional internal combustion engines (ICE) to electric vehicles (EVs) has the potential to greatly reduce the overall energy demand of the transport sector. Our previous work has shown that a transition to EVs in a combination with a modal split from air and road to rail transport can reduce the energy consumption in Croatia by 99 PJ, which is approximately 59%, by the year 2050 when compared to the business as usual scenario. The goal of this paper is to model the hourly distribution of the energy consumption of EVs and use the calculated load curves to test their impact on the Croatian energy system. The hourly demand for the transport sector has been calculated using the agent-based modelling tool MATSim on a simplified geographic layout. The impact EVs have on the energy system has been modelled using EnergyPLAN.

Key words: Electric vehicles, Demand side modelling, Agent-based modelling, Electrification of transport, EnergyPLAN, MATSim

1. Introduction

The transport sector represents a serious energy consumer in most energy systems across the EU and wider. In Croatia for example, the transport sector accounted for 32.8% of the final energy consumption in 2011 making it the second most energy demanding sector right after buildings with 43% [1]. In the last decade, the final energy demand of the transport sector has increased by approximately 70% due to a verity of reasons including economic growth and large investments into a modern highway infrastructure [2]. These numbers demonstrate a large potential for energy savings related to it especially if we consider the increase in transport demand and low efficiency of standard internal combustion engines (ICE).

As it has already been demonstrated in our previous work [2], a widespread electrification of the personal vehicle fleet could reduce the total final energy demand of the transport sector in

Croatia by roughly 53% by the year 2050 when compared with a business as usual scenario. This represents a saving of 89 PJ of energy. If a modal split from road and air to rail transport is taken into account as well, this savings could be increased to 59% or 99 PJ. Other authors have already demonstrated the benefits that electrification can have on an energy system when it comes to greenhouse gas emissions [3], [4] and [5] but in order to properly asses their impact on a system as a whole an hourly analysis has to be implemented. This is necessary to accommodate for the increase of peak demand of electricity and the potential for the utilization of batteries of parked electric vehicles (EVs) as energy storage mediums that can increase the possibility for the penetration of intermittent renewable energy sources (RES). The importance of the implementation of energy storage technologies on the penetration of intermittent RES has already been discussed by several authors [6], [7] and [8].

There are a variety of approaches already available for the forecast of the annual energy demand of the transportation sector such as the ones described in [9], [10] and [11] but, as it has been already stated earlier, an hourly distribution is needed here. To accommodate for this, agent based modelling (ABM) has been utilized in the case of this work. The ABM is a relatively young area of research applied widely so there are several definitions on basic concepts. Commonly, in ABM a system is modelled as a collection of autonomous decision-making entities called agents. These entities are placed into an environment and are able to autonomously react to changes in the environment. This definition in turn implies the agents' capability of sensing the environment and effecting (actuating) in order to interact with the environment and change it [12]. In other words the agent entities are able to capture information from the environment and percept the items of acquired information, and then act accordingly. In turn, these actions affect the environment; provoking further interactions from other entities. From the paradigm viewpoint, the ABM can also be seen as microscopic, i.e. per-entity modelling, as opposed to macroscopic modelling where the integral system is being modelled. Furthermore, the separation of agents and their environment indicates the inherent distributable characteristics of ABM. Several classifications of ABM consider the environment, e.g. its observability (i.e. whether an agent can gather the complete state of the environment), or whether the environment is deterministic or stochastic etc. The definition of agent considers a certain degree of autonomy. The agents may autonomously execute various behaviours appropriate for the system they represent (e.g. purchasing, consuming, and selling). An *intelligent* agent exhibits proactiveness, reactivity and social behaviour: it is able to act towards a certain goal, it can respond to changes in the environment and it is able to interact with other agents [13]. The intelligent agent research has largely emerged from artificial intelligence and one is able to build highly complex internal structures of the agents. Generally, ABM only requires the agents to place reasonable decisions about actions to be performed. Thus even with relatively simple agent definitions, ABM can deliver repetitive and competitive interactions between agents that result in complex behaviour patterns, and this is one of key advantages of ABM: it allows the emergence of complex behaviour patterns from relatively simple per-entity models. The ABMs have been successfully used in areas ranging from economics [14] and social sciences [15] to biology and diverse engineering areas [16]. In general, when the system being modelled is complex, modular and decentralized, changeable (i.e. not statically defined), and defined at the time of design, ABM is a well-fitted method of modelling.

The Goal of this work is to model the hourly distribution of the transport energy demand and utilize that data to analyse the impact personal EVs can have on the potential for the penetration of wind and PV power in an energy system. The agent based transportation system modelling tool MATSim [17] has been used to generate said distribution and the

EnergyPLAN [18] advanced energy system analysis tool has been utilized to model Croatia's energy system and conduct the analysis.

2. Methodology

The methodology of both the processes of obtaining the hourly energy demand curves for the road transport sector in MATSim and the energy system modelling in EnergyPLAN have been explained in this chapter.

2.1. MATSim

In order to properly analyze the interaction between personal EVs and the electricity grid an hourly distribution of the energy demand of personal road vehicles had to be created first. As stated above, the ABM is a well-fitting method for transport modeling: there are numerous agents whose decisions and behaviours, guided by their own intrinsic rules, that by interacting among them and with the environment impact the whole transportation system on a larger scale. Furthermore the transportation system conditions are not fixed. The application of ABM in the modelling of transport is diverse. In [19] the authors present a TAPAS system for simulation of transport chains, aimed towards transport-related policy and infrastructure measures. Similarly, in [20], the authors deliver insights in the use of agent-based modelling of transport logistics. This paper focuses on the simulation of urban transport, such as the study presented in [21], where the authors present a study on driver behaviour in congested streets of the city of Brisbane. Several tools for agent-based modelling of such urban traffic exist. NISAC FastTrans [22], developed at US Los Alamos National Laboratory is a discrete, event-based simulator designed to study the impacts of infrastructure components in crisis management and dynamic prioritization. MAINSIM [23], Multimodal Inner-city Simulation Tool is a tool developed in Goethe University in Frankfurt, Germany, aimed towards using map information directly. It is an actor-based simulation system. COS-SIM [24] is an open source tool for agent-based micro simulation of traffic flows, directed primarily towards tuning of the traffic control devices.

For the simulations in this paper, MATSim [17] was chosen as a simulation tool. The MATSIM model provides a framework to implement large-scale agent-based transport simulations. It is exceptionally modular: demand modeling, mobility simulations, replanning, controller module and analysis modules are provided. These modules can be used in combination or stand-alone. The MATSIM model is open-source, cross-platform and highly customizable, since its Java source code is freely available online. Thus MATSIM offers extensibility and allows the user to add additional functionalities to its modules and tailor the MATSIM for a particular problem.

A key feature of MATSIM is agent-based, multi-modal simulation of daily mobility behaviour. The MATSIM simulations utilize behaviour definition for single persons ("agents") to track and model the system behaviour on the whole. In the case of personal EV-based mobility, the aggregated behaviour is visible as an additional electricity demand and for this reason, along with the flexibility to include the EV-related specifics, MATSIM was selected as an appropriate tool for this paper.

The MATSIM simulation architecture [17] makes it particularly suitable for policy-making issues, and it has been successfully used in tasks such as assessing the emission impact due to household travelling [25] optimizing taxi service [26], determining policies on traffic planning [27], [28] etc.

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2.2. EnergyPLAN

EnergyPLAN is a deterministic input output computer modelling tool that creates an annual analysis of an energy system on an hourly level. It requires a wide range of input data including the total annual demands and hourly demand curves for electricity, installed capacities and efficiencies of different types of energy producers (both renewable and non-renewable) and energy storage technologies, fuel mix, hourly distribution of energy production from intermittent sources like wind, solar and small hydro, the energy demands for different sectors including transport, hourly distribution of transport energy demand, vehicle to grid connection capacities, different regulation strategies and so on. The results of the model include energy balances, annual and hourly energy production by source and the critical excess of electricity production (CEEP) present in the system, fuel consumptions by fuel type, total cost of the system, CO_2 emissions and so on.

EnergyPLAN is a well documented tool that specializes in the large scale integration of RES in energy systems [29] and [30], the optimal combination of RES [31] and the implementation of CHP units in energy systems [32]. It has already been used to recreate many different energy systems and devise numerous energy scenarios. For example, authors of [29] and [33] used the model to simulate different scenarios for the Macedonian energy system. In [32] and [34] EnergyPLAN has been used to model the Danish energy system and to analyze the potential for the integration of RES. The authors of [35] used both the EnergyPLAN and the H_2RES [36] models to recreate the Croatian energy system and plan a 100% energy independent scenario. EnergyPLAN has already been used to analysis of the impact of the transport sector, especially electric vehicles, on an energy system [37] and [38] in the past.

3. Case study for Croatia

The data gathering and processing and the development of the case study for Croatia using both MATSim and EnergyPLAN has been explained here.

3.1. Hourly distribution of the transport energy demand

In order to create an hourly energy demand curve for the Croatian road transport sector, more precisely personal vehicles, 4 individual distributions have been created for the cities of Zagreb, Rijeka, Split and Osijek. The sum of the four curves is used to represent the distribution for Croatia.

Inputs required by the MATSim are divided into the following categories:

- population: provides agent's identification (agent ID number), age, working municipality and longitudinal and lateral coordinates of home location
- activity plan: tells agent at which location (*work*, *home, leisure*, *shopping*) they should be at the specified time
- network: provides the detailed network for each city under the consideration and only the main roads outside the city limits
- facilities (optional): provides the longitudinal and lateral coordinates of non-home locations

The quality of the solution obtained by MATSim will be closer to reality if the input data resides on real-world observations. The best possible scenario is when each single agent represents one surveyed person, but this is highly impractical and impossible to get. Therefore, input data has to rely on survey conducted amog a limited number of surveyed people and set of data that is usually available in aggregated form. In order to reduce the number of input data and simplify the preparation of MATSim inputs, the following assumptions are used:

- the only activities are home and work
- leisure is assumed to be on the same locations as work
- there are no holidays within the year

In order to find the population and activity plan inputs for the four biggest Croatian cities, the spatial distribution of *home* and *work* locations were estimated based on the socio-demographic data, available as aggregated values at the municipality level, building density per area and the official addresses of registered companies. Since the municipalities are too big to provide a sufficiently fine resolution of *home* and *work* locations, they are further divided into 200 x 200 m rectangular cells. At this resolution, the *home* and *work* locations can be found and overlaid over the road network, as presented in Figure 1 for the case study of Croatia.

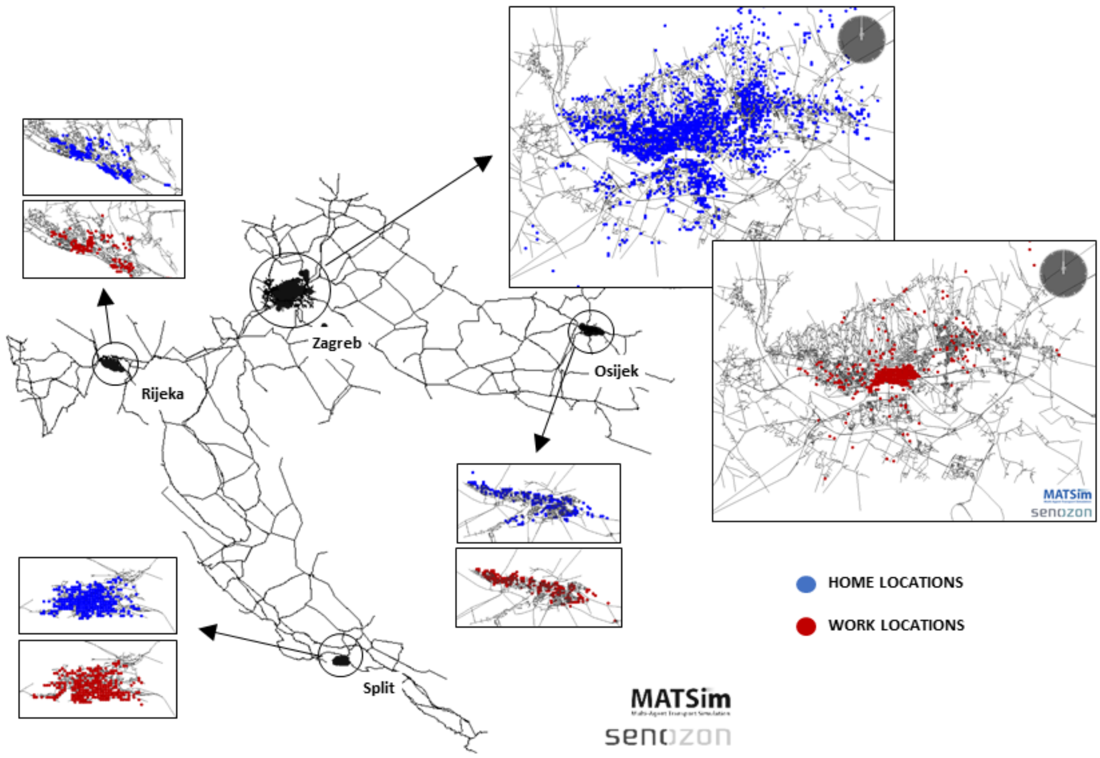

Figure 1 Network of Croatia's main roads coupled with the detailed road network in the four biggest cities overlaid with the facilities presenting agent's *home* and *work* activity locations.

Aggregated values for population and number of households for city municipalities can be found at the official web pages of each city [39], [40], [41] and [42] and boundaries of each city municipalities can be found as polygon data from Google Earth [43].

The buildings density per area is estimated from the percentage of each cell area covered by the building polygons, divided by the total area of the cell. Buildings polygon data are taken from the Geofabrik online database [44]. The addresses of companies are extracted from the Croatian Chamber of Economy (CoE) [45].

Table 1 Aggregated socio-demographic input data for Croatia's four biggest cities

	Zagreb (ZG)	*Split (ST)*	*Rijeka (RI)*	*Osijek (OS)*
area limits in WGS84 coordinates (estimation)	46.021N 15.534W 45.665S 16.392E	43.534N 16.382W 43.498S 16.512E	45.386N 14.3348W 45.307S 14.520E	45.584N 18.596W 45.525S 18.776E
No. of municipalities	17 [39]	27 [40]	34 [41]	15 [42]
No. of employed (2011 census) [46]	322.256	63.561	50.494	38.786
% of employed driving a car	62 [47] 77 [48]	62(est.)	62(est.)	62(est.)
Estimated number of agents travelling by car	199.798	39.407	31.306	24.047

Total number of employees is provided by the Croatian Bureau of Statistics [46]. Total number of agents for each city municipality is estimated as a total number of employees multiplied by a percentage of employees having personal vehicles as a mode of transport [47].

Activity plan for each agent should provide the coordinates of each activity and their time series during the day. Activities are different for the work day or weekend. In this work, the only activities are *home* and *work*. *Home* location for each agent is found among the available cells taking into account the probability of the building density. An example for the city of Zagreb is given in Figure 2 with a resolution of 200 by 200 m.

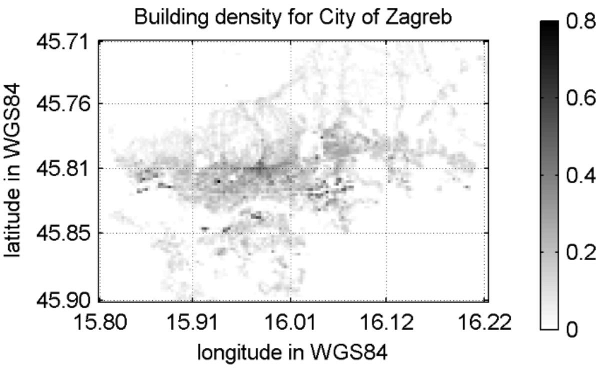

Figure 2 Distribution of the building densities in the city of Zagreb

Finding the *work* location for each agent is divided into two steps. In the first step, the municipality of the work location is found from the solution of the origin-destination (O-D) matrix, whose rows represent probabilites of work municipalities and it's sum of column values corresponds to toal number of registered businesses for each municipality, normalized by the total number of businesses. The O-D matrix is solved by the iterative proportional fitting (IPF) algorithm. The penalty function for the IPF procedure is the interpolation between the O-D matrix distance values between municipalities and the daily driven kilometres from the input survey [48], Fig.3. The survey has been conducted by the Energy Institute Hrvoje Pož ar for the city of Zagreb on a sample of 361 people. In the second step, the exact cell of the *work* location cell is found from the building density within the target municipality, by following the same procedure as in the case of finding the *home* locations.

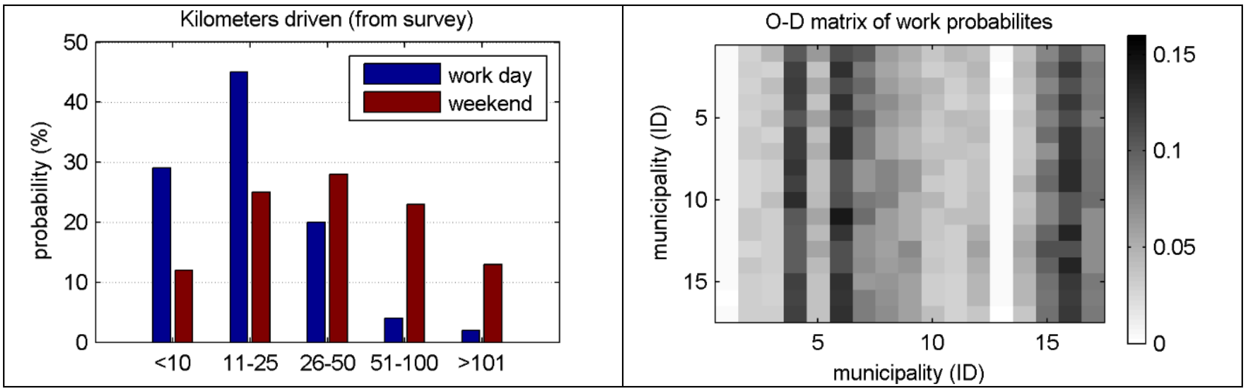

Figure 3 average daily driven kilometres obtained from the survey (left) and the resulting O-D matrix of the probabilities for work municipalities for the City of Zagreb (right)

From Figure 3 three municipalities can be recognized as municipalities with the most registered businesses, which follows directly from the CoE inputs.
Time series are constructed from the assumption that departures from the *home*, *work* and *leisure/shopping* locations follow a normal distribution. Typical distributions for the work day and the weekend are presented in Figure 4.

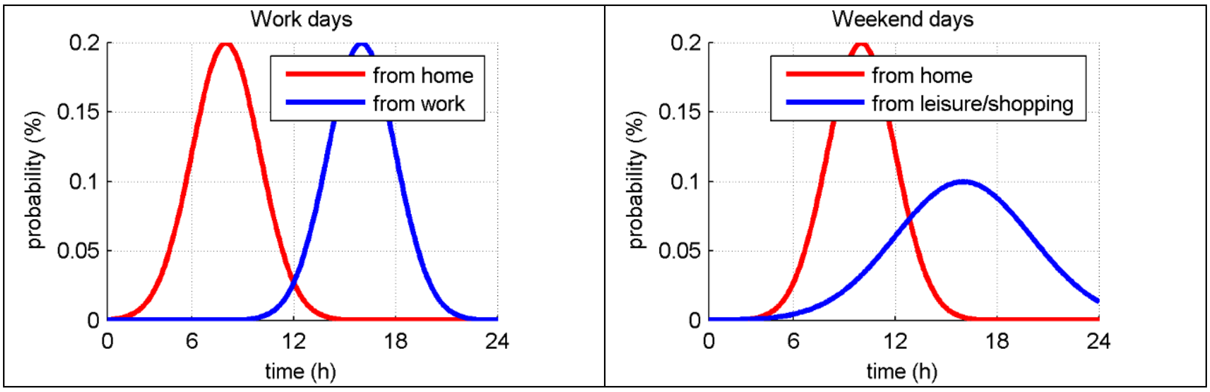

Figure 4 Time series probabilities for activities home, work and leisure/shopping for work day (left) and weekend (right)

MATSim utilizes the time series, O-D matrix and the developed transport network to generate the agent's behaviour and with that the hourly distribution curve. The difference between the input time series and output distribution is presented in Figure 5.

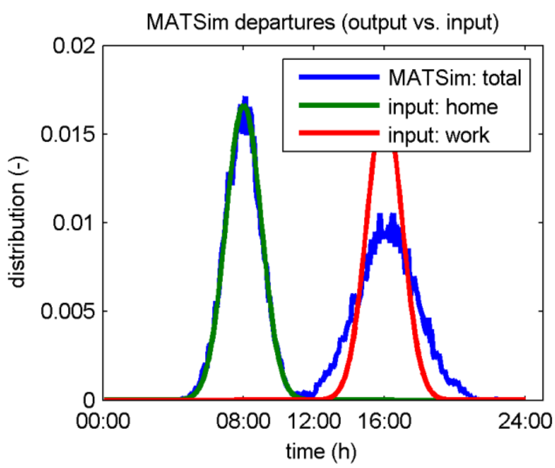

Figure 5 Difference between the input time series and output distribution

The network is extracted from the OpenStreetMap data, region Europe, sub-region Croatia, downloaded from the Geofabrik web server [44].

3.2. Modelling of Croatia's energy system

In order to analyse the impact EVs have on the grid a reference model of Croatia's energy system has been created in EnergyPLAN. As it has already been mentioned, EnergyPLAN requires a wide variety of inputs. The fuel mix of the large thermal power plants as well as the energy use of the individual sectors has been adopted form the International Energy Agencies (IEA) web site [49]. The hourly electricity load has been taken from the web site of the European Network of Transmission System Operators for Electricity [50]. Meteorological data including global insolation and wind speeds have been taken from Meteonorm [51] and used to calculate the hourly production from wind power and PV. The obtained annual figures were then compared with the data available on the IEA website [49]. These data is presented below in Table 2. The installed capacities of the installed power plants have been taken from [1] and [52] and the statistical information related to the number of personal vehicles from [53]. A minimal grid stabilization share, the minimum production of electricity from power plants capable of providing ancillary services in relation to the total production of electricity, has been set to 30% in all scenarios. The minimal capacity of thermal power plants (PP min) of 42% has been assumed. The technical regulation strategy number 2 has been used "Balancing both heat and power demands". The impact of different optimisation criteria on energy systems has been discussed in [54] in great detail. The CO_2 content of the different fuels has been taken from [33].

In order to validate the created scenario, several parameters calculated by EnergyPLAN have been compared to the ones listed on the IEA web site. Table 2 presents the comparison of the results obtained from EnergyPLAN and the data from the IEA [49]. As the table shows, there is a difference of 3.5% between the calculated CO_2 emissions and the ones listed by the IEA. This is due to the emission factors that the IEA uses. The electricity production from fossil fuels, hydro and renewables is almost identical for both cases. The great difference between the electricity produced from nuclear energy and the import and export of electricity is due to the way the IEA regards the nuclear power plant in Krško, Slovenia. It is partially owned by Croatia and partially by Slovenia but since it is located outside of Croatia's borders, the electricity it produces and distributes to Croatia is regarded as import. If we add up the electricity generated by it with the electricity import and export, the resulting values are almost identical.

Table 2 Validation of the EnergyPLAN model

	EnergyPLAN	Iea.org [49]
Total CO_2 emissions	18.11 Mt	18.77 Mt
Electricity produced from fossil fuels	6.00 TWh	6.01 TWh
Electricity produced from hydro energy	4.63 TWh	4.62 TWh
Electricity produced from renewables	0.20 TWh	0.201 TWh
Electricity produced from nuclear	2.97 TWh	0 TWh
Electricity import	4.73 TWh	8.730 TWh
Electricity export	0.01 TWh	1.033 TWh
Import – export + nuclear	7.69 TWh	7.697 TWh

4. Results

4.1. MATSim results

Results obtained from MATSim are time series of kilometres that vehicles travel for each day of the week for each of the four cities taken into consideration, Figure 6.

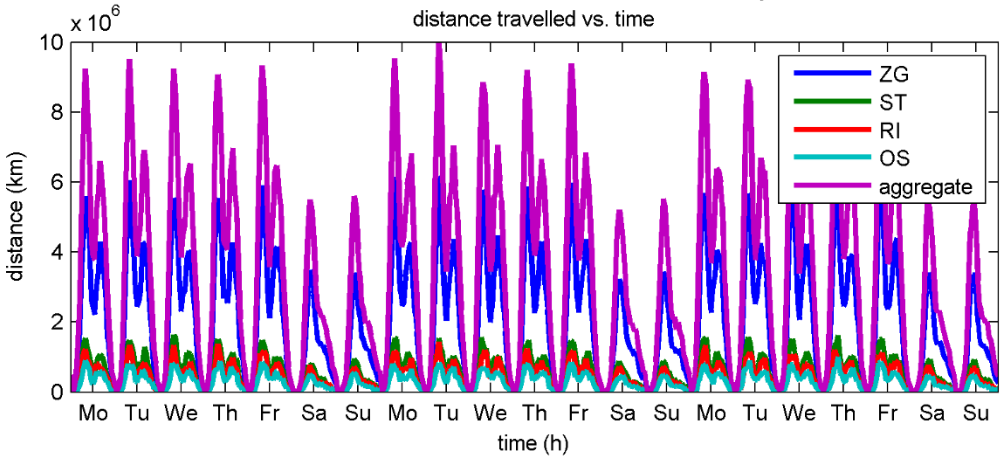

Figure 6 Output from MATSim: time series of kilometres driven for three weeks

The time series of travelled distance is strongly following the time series of prescribed activities. The city of Zagreb is the most dominant in the aggregated value.

4.2. EnergyPLAN results

In order to analyze the impact of EVs on Croatia's energy system, 12 scenarios have been devised. The first 6 scenarios analyse the potential for the penetration of wind power for a baseline scenario with EVs and 5 scenarios with EV penetration of 10%, 20%, 30%, 40% and 50%. The second set of 6 scenarios analyse the same scenarios but for PV penetration. The wind and PV penetrations are varied from 0% to 50% of the total electricity demand (excluding EVs), meaning that the production of electricity from wind or PV equals 0% to 50% of the total electricity demand excluding EVs, with a step of 5%.

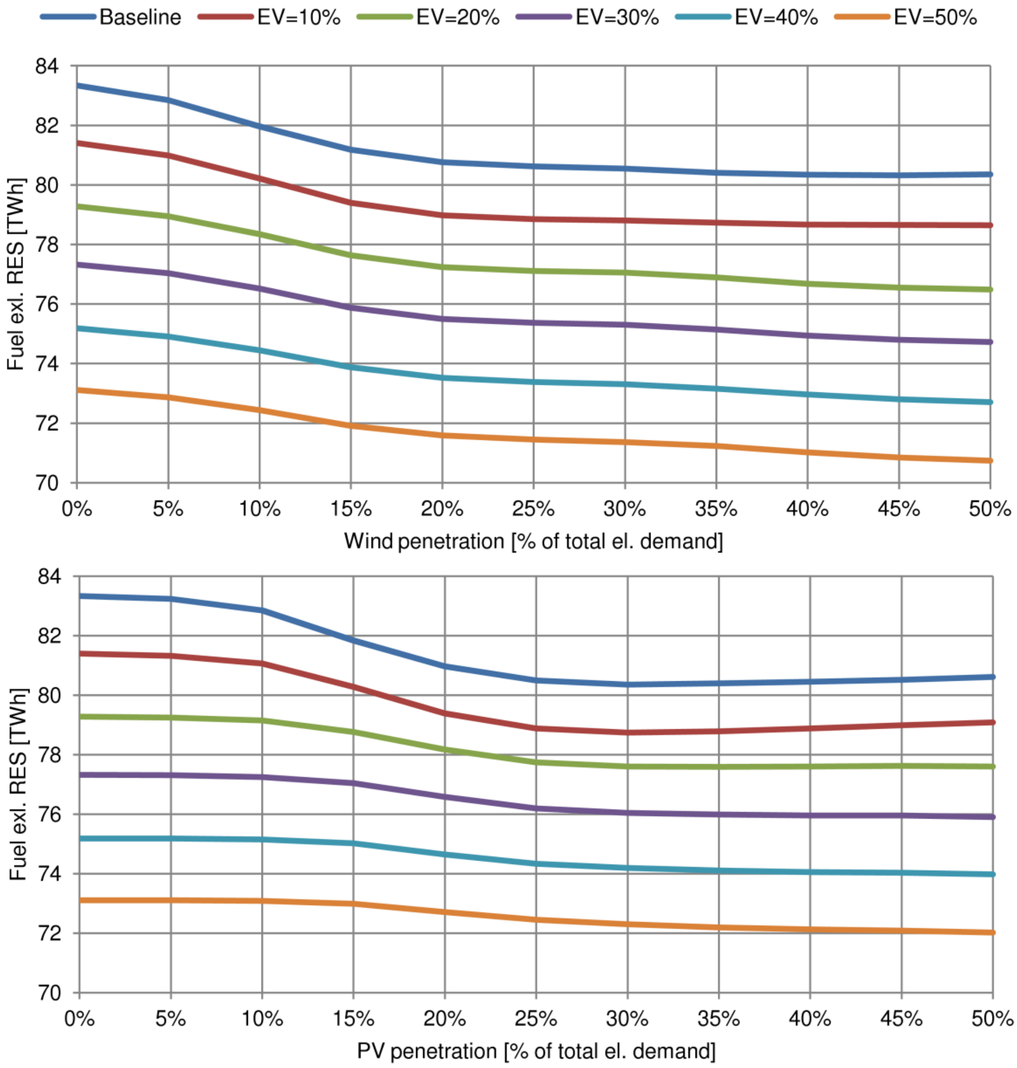

Figure 7 Fuel consumption excluding RES for scenarios with wind (top) and PV (bottom)

Figure 7 presents the total fuel consumption excluding RES for the six scenarios with wind (top figure) and PV (bottom figure). As it is expected, the scenarios with a higher penetration of RES have lower fuel consumption and the increase in the penetration of EVs also has a positive effect on its reduction. This is primarily due to the fact that EVs are considerably more efficient, upwards of 300% more in some cases, but also because the increase of their penetration presents a storage capacity for excess electricity and thus can increase the potential for the penetration of intermittent RES like wind and PV. In this work the average efficiency of vehicles with ICEs was presumed to be 1.5 km/kWh and for EVs 5 km/kWh. A 50% share of EVs can reduce the total fuel consumption of the whole system (including all sectors not just energy and transport) from the base value of 83.34 TWh to 73.11 TWh which is a difference of 10.23 TWh or 12.3%. Higher penetrations of RES do not have a significant impact on the reduction of fuel consumption; in the baseline scenario a 50% penetration of wind power reduces the total fuel consumption from the base value of 83.34 TWh to 80.35 TWh, a difference of merely 3.5%. The results are fairly similar for PV with a reduction of 3.26%. This is true because of the high dependence on imported electricity which doesn't register as fuel consumption. When such import is replaced with electricity from RES, fuel consumption of the system stays almost unchanged.

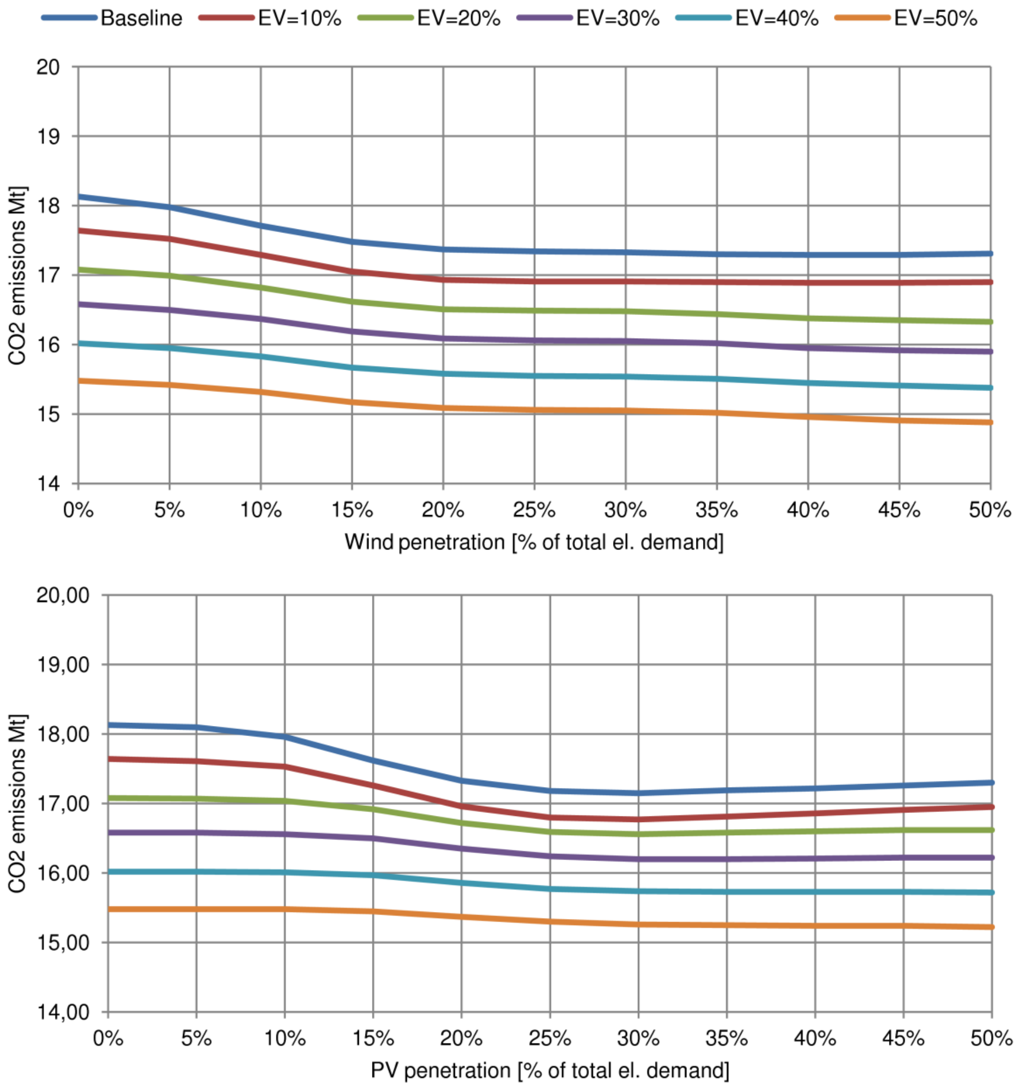

Figure 8 CO_2 emissions for scenarios with wind (top) and PV (bottom)

Figure 8 presents the annual CO_2 emissions for the six scenarios with wind (top figure) and PV (bottom figure). The data on the figures closely follow the trend of the fuel consumption presented in Figure 7, which is to be expected A 50% share of EVs has reduced the total annual CO_2 emissions of the whole energy system, again including all sectors, from the initial value of 18.13 Mt to 15.48 Mt, a reduction of 14.6% in the presented scenarios. Again, similar to the results presented in the previous figure, the penetration of RES doesn't affect the CO_2 emissions significantly for the same reason it doesn't influence fuel consumption. Both for a wind and for a PV penetration of 50% the total CO_2 emissions are reduced to 17.3 Mt, a reduction of 4.6%.

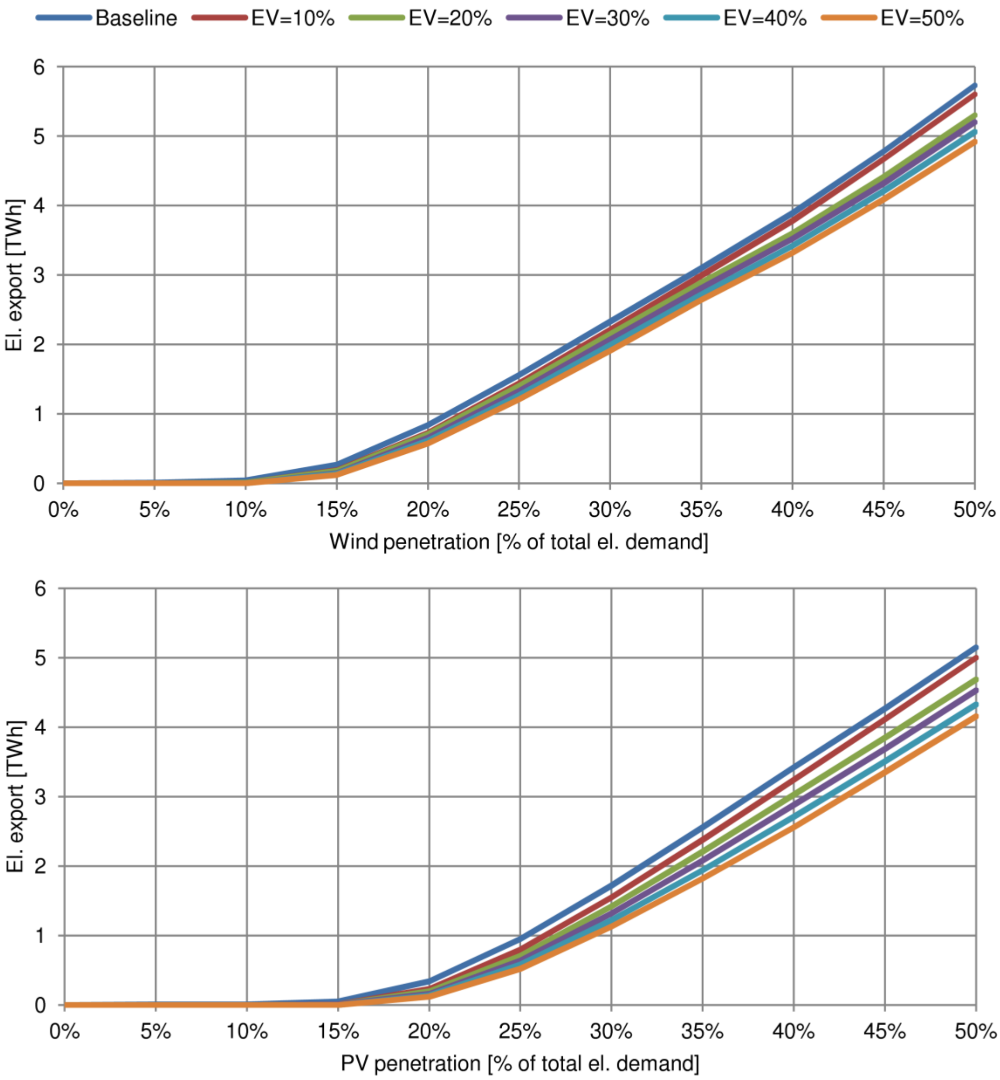

Figure 9 Export of electricity for scenarios with wind (top) and PV (bottom)

Figure 9 presents the total annual export of electricity, again for the scenarios with wind (top figure) and PV (bottom figure). It can be observed from the figures that a penetration of wind higher than 10% or PV higher than 15% will force the system to export some electricity. In the case of the scenarios that include wind power, its penetration of 15% with no EVs resulted in the export of 0.27 TWh, or 0.12 TWh for an EV share of 50%. In the case of a 50% wind power penetration the figures go up to 5.73 TWh with no EVs and 4.92 TWh with an EV share of 50%. The results are similar for the scenarios with PV, although the export is somewhat reduced. For the case of a PV penetration of 15% and no EVs, the electricity export equals 0.05 TWh. There is no export present in the same case but with a 50% share of EVs. For a PV penetration of 50% and no EVs, the electricity export equals 5.15 TWh and 4.16 TWh for an EV share of 50%. The difference in the exported electricity for a scenario with 50% wind penetration with no EVs and with 50% EVs is 0.81 TWh or roughly 4.4% of the total electricity demand, excluding EVs, of Croatia in the year 2011. In the case of PV the same difference is 0.99 TWh or roughly 5.3% of the total electricity demand excluding EVs.

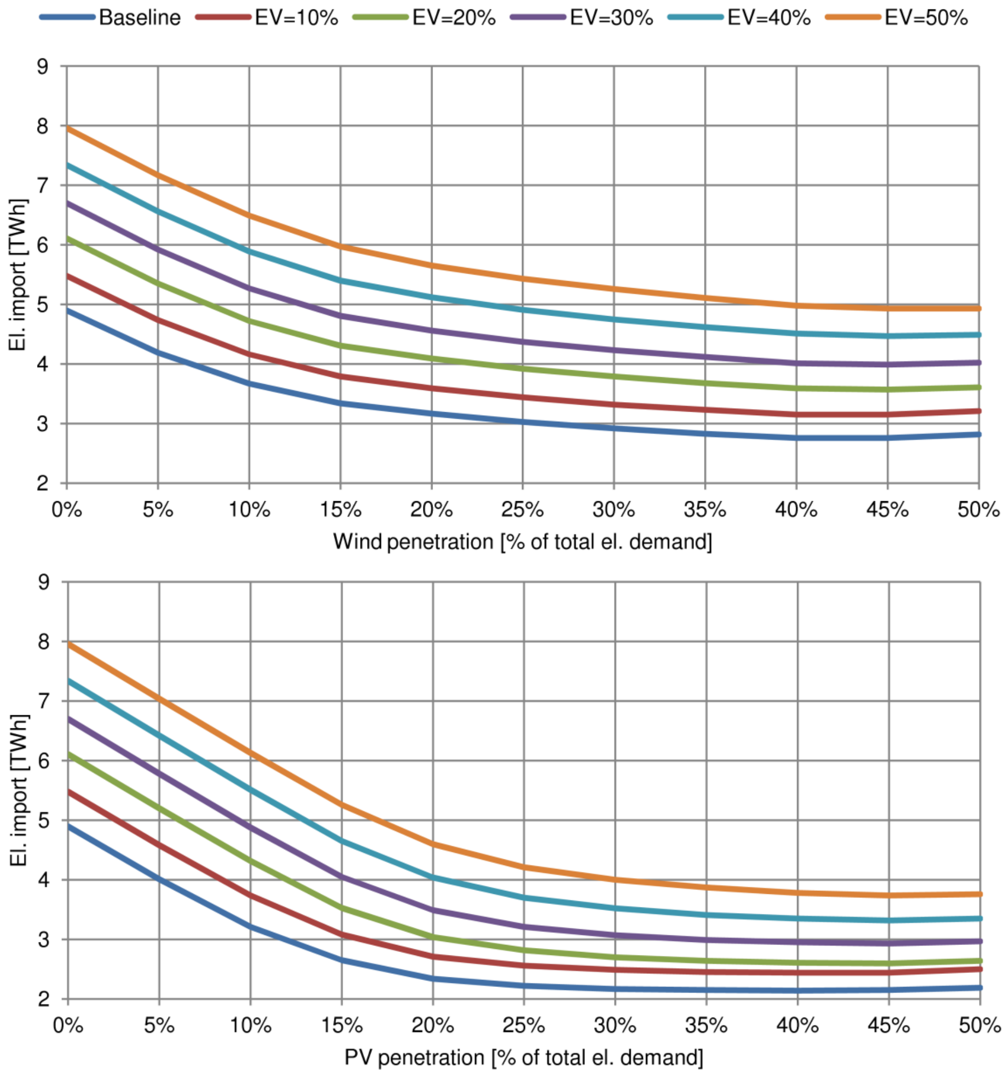

Figure 10 Import of electricity for scenarios with wind (top) and PV (bottom)

Figure 10 presents the total annual import of electricity for the scenarios with wind power (top figure) and PV (bottom figure). Since Croatia already imports a significant amount of electricity every year, 8.73 TWh in the year 2011 which is equal to 47% of the total electricity demand of that year [49], the additional demand posed by the EVs would naturally increase these values. This is evident from the presented figures. A 50% share of EVs increased the necessary import of electricity from the base value of 4.9 to 7.96 TWh.

5. Sensitivity analysis

In order to determine the impact that the detailed analysis of the transport demand has on the energy planning results a sensitivity analysis has been conducted comparing the hourly distribution obtained using MATSim, presented by Figure 6, and a constant distribution. CEEP has been compared for the two curves for three different penetrations of EVs (10, 30 and 50%) and for a wind power penetration ranging from 30% to 50% with a step of 5%. Wind power penetrations below 30% are not analysed since CEEP is always 0 for these case in the created scenarios. The results of the sensitivity analysis have been presented in Table 3.

Table 3 Results of the sensitivity analysis

	EV=10%		EV=30%		EV=50%	
Wind	MATSim	Constant	MATSim	Constant	MATSim	Constant
30%	0%	0%	0%	0%	0%	0%
35%	8%	8%	2%	2%	0%	1%
40%	33%	33%	15%	17%	9%	11%
45%	77%	78%	49%	53%	36%	42%
50%	132%	133%	98%	104%	81%	90%

As the results in Table 3 demonstrate, the difference for a low penetration of EVs is very small between the generated distribution curve and a constant line. For an EV penetration of 10% the difference between the two distributions is only about 1%. The difference becomes much more significant at 30% and 50% EV penetration. For 30% the difference varies from 6% to 12% and for 50% it varies from 10% to 18%.

6. Conclusion

Agent based modelling can be a strong tool for the modelling of the hourly distribution of energy demand of the transport sector. As it has already been stated, the quality of the results of the modelling will be highly dependent on the quality of the inputs.

The obtained hourly energy demand curves for the Croatian road transport sector has been used in the EnergyPLAN tool to analyse the impact of electric vehicles on Croatia's energy system and the potential for the increase of the penetration of wind power and PV. The results have shown that the electrification of the road transport sector can help reduce the fuel consumption by 12.3% and CO_2 emissions by 14.6% for the case of no renewables and a 50% share of electric vehicles. These numbers are even greater when higher penetrations of renewables are taken into account. A conducted sensitivity analysis has shown that the hourly distribution of the EV demand can have a strong influence on the obtained results at high levels of EV and intermittent RES penetration. In our case the difference in CEEP was up to 18% between the distribution generated using MATSim and a constant demand.

Future work related to this paper will include the development and utilization of a detailed survey aimed at the energy consumption of personal transport and the validation and further refinement of the obtained distributions.

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