Simulations of all electric vehicles on fixed routes

R. Fainti, A. Nasiakou, E. Tsoukalas, M. Vavalis

Electrical and Computer Engineering Department,
University of Thessaly, Volos, GREECE.

and

Institute for Research & Technology of Thessaly,
CERTH, Volos, GREECE.

Email: [fainti,nasiakou.tsoukala,mav]@inf.uth.gr.

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Abstract

This paper presents, the design, the implementation and the preliminary experimentation of a simulation framework for investigating the effectiveness of battery powered vehicles under the assumption that they follow a route which is either predefined or its basic characteristics can be obtained at almost real time. In particular we would like to investigate the feasibility of all electric, battery only powered trains whose batteries are charged at appropriately located renewable energy sources. We have develop our web based, open software simulation platform by utilizing and extending Gridlab-D, a power system modeling and simulation environment and by incorporating data from various sources. Results from preliminary simulations of real life scenarios are presented and analyzed.

Keywords: battery powered vehicles, load management, optimization, power system control, power system reliability, smart power grids, simulation.

1 Introduction

The design and development of full electric vehicles have already proved their potential and attracted the interest of many stakeholders who invest an ever increasing amount of resources. Their approaches vary from accurate but costly and time consuming prototyping and physical testing to less accurate but much faster and more flexible computer modeling and simulation. In this paper we restrict ourselves in the modeling and simulation and focus on a particular type of full electric vehicles that enjoy several attractive characteristics at least for particular types of vehicle and route configurations.

The vision of all-electric vehicle (AEV) that uses no gasoline or diesel fuel is not new. Till recently batteries that store enough electricity to give a vehicle acceptable driving range were expensive, large, and heavy. Therefore affordable and reliable AEVs required technological advances mainly in energy storage. This lead to compromised solution, hybrid vehicles, diesel engine-powered vehicles that use batteries to store energy during regenerative breaking and use and provide it during acceleration. Such vehicles are currently widely used with significant commercial impact on the market. Nevertheless, there are enough evidences that soon technology will provide new attractive options that will pave the way for AEV. AEVs have already appeared and production even on a commercial scale have already started for family-size automobiles at least. The emerging, from both the industry and the research sectors, technologies promise advanced automotive batteries soon, which will surely lead to cheaper hybrid electric vehicles. We may as well claim that many of these hybrid cars will be eventually replaced by AEV.

The main objective of this paper is to examine the feasibility of exploiting recent technological developments and emerging best practices in the area of both hybrid and all-electric cars for other types of larger vehicles like ships and trains. We focus on existing regional rail links with specific features such as the relative brevity of the route, lack of adequate existing electricity infrastructure and the possibility of cartel activities related to renewable energy, particularly solar.

In particular this study focuses on the design and implementation of a robust, effective and user friendly simulation engine that allows accurate in-depth analysis of the qualitative and quantitative effect of a plethora of characteristics (e.g. weight, speed, number of passengers, air conditioning, lighting, type and capacity battery type and size of PV, wind turbines,

weather prediction / climate ...) of AEV. We restrict ourselves on medium size public transportation vehicles that run based solely on super-capacitors and on battery packs that can be loaded and / or replaced at specific rail stations of the route where photovoltaic or/and wind power systems might be available to recharge them. These trains do not require a network cable to electric currents of high or medium voltage, which besides their high installation cost might have particular, possibly heavy, maintenance and security requirements.

Our results hold for (and our simulation engine can accommodate) any kind of vehicles that travel on a medium length and, to some extent, predefined route. Nevertheless, in this paper we focus on a particular but rather representative kind of vehicles; regional trains. So our study is mainly a preliminary investigation effort concerning the design of a medium size all electric train. Specifically we would like to investigate whether the technologies that drive the success of the existing AEVs, and in particular all electric cars, may lead us to a new generation of All Electric Trains (AETs) that take full advantage of possible alternative energy sources on route.

Specifically our paper contains

- An up-to-date state-of-the-art investigation which shows that although several similar efforts exist around the world none of them is capable of drawing concrete final conclusions or assisting us to develop a robust road-map towards commercial AEV.
- A description of the design decisions taken and the implementation practices followed to develop our simulation engine which utilizes GridLAB-D a new power distribution system simulation and analysis tool.
- A set of experimental results concerning trains currently operating on two routes in central Greece that
 - show that it is technologically possible to even convert conventional operational trains to AETs
 - allows us to recommend further technological and financial feasibility studies.

The rest of this paper is organized as follows. In the next section we outline our motivation, discuss certain related concepts, and briefly present

the technologies associated with batteries, photovoltaic panels and wind turbines. In section 3 we provide an overview of related to our study efforts. In section 4 we describe our modelling decisions, our computational framework and our implementation characteristics. Section 5 contains a description of our experimental test cases and a presentation of our simulation results. Our conclusions together with a list of research and development issues that are beyond the scope of this paper can be found in section 6.

2 Background

On the basis of the recent undisputed success of primarily the electric family-size automobiles our efforts have been motivated by the fact that other type of vehicles exhibit additional attractive properties as far as their electrification concerns. Trains and ships, for example, enjoy much lower sliding friction than cars and therefore require much less energy per passenger (almost 1/3 for trains). Our work is further motivated by the fact that the use of alternative energy sources has become increasingly prevalent with the spread of the green movement and the widely accepted prediction that the blooming of the battery technologies market in the next decade will be astonishing.

Let us first properly define the often overloaded term "all electric vehicle" by adopting the following definition from Wikipedia.

An "all-electric vehicle (AEV)" known also as "battery-only electric vehicle" is a type of electric vehicle that uses chemical energy stored in rechargeable battery packs. They use electric motors and motor controllers and have no internal combustion engines, fuel cell, or fuel tank.

We furthermore assume that the basic components of a AEV are an electric engine, a control unit, an energy storage system, a battery management system, a battery charger system and a braking system in order to feed back the entire system.

In our study we assume that:

The storage system is based on the two most common technologies; lithium ion batteries, ideal for high energy capacity, and ultra-capacitors (see next section), ideal for high power discharge and frequent cycles. A set of batteries are on the vehicles providing propulsion while additional

set appropriately located at recharging stations along the route of the vehicles.

The battery charger system contains a set of renewable energy sources like photovoltaic panels [Kel12] and wind turbines whose primary objective is to be able to provide as much energy needed for the vehicles to complete their journeys. This system may of course provide the additional energy to the train stations themselves or to the power Grid if necessary.

The battery control system which continuously monitors the charging status of all the batteries and decides where and when the exhaustive on board batteries will be replaced.

Various types of all electric vehicles may be considered. All electric ships [ZN13] and all electric aeroplanes¹ share common with the cars features (low traction) but differ significantly (regenerative break acceleration) with respect to several characteristics. All electric buses of various types and sizes also exist in several countries with the first appeared a decade ago. The ones that come close to our study are the heavy commercial buses. All such electric commercial bus (at Seoul) is carrying Li-on battery and regenerative braking and could run to 84 km in a single 30 minutes charge with maximum speed of 100 km/h. Another typical example are the costly Prasarana prototype electric buses with a range of almost 300 Km. They are expected to become soon operational as part of the Malaysian green environment initiatives.

It is worth to mention here that almost every Vehicle Routing Software has web services² which allow to obtain information from various sources like the status of the charging batteries and beyond.

We argue in order for the above vehicles to become as much as possible independent of the power grid and at the same time be economical effective and environmentally friendly proper experimentation is need. Some of the questions to answer are: how big should be the batteries, the Photovoltaic panels, how often we need to replace etc. This will allows to design a possibly optimum configuration of the train itself, its route, its energy storage, its charging system so it is in balances with other various parameters associated with weather conditions, passenger and cargo loads etc.

¹<http://live.solarimpulse.com/>

²http://www.orms-today.org/surveys/Vehicle_Routing/vrss.html

Battery Type	Energy/weight Watt-hours/Kg	Energy/volume watt-hours/L	Power/weight watt/Kg	Energy/US <i>watt – hr</i>
Lead-acid	30-40	60-75	180	4-10
Nickel-Zinc	60-70	170	900	2-3
Lithium-Ion	160	270	1800	3-5
Lithium-Polymer	130-200	300	to 2800	3-5

Table 1: Essential characteristics of rechargeable batteries [http://www.allaboutbatteries.com/electric_cars.html]

For this we have developed a simulation engine using the GridLAB-D³ simulation environment [CSG08], created by the US Department of Energy at Pacific Northwest National Laboratory. More information about GridLAB-D will be given in the next section. Our simulation engine is developed so that if the total amount of energy required for the vehicle to reach a particular station where the batteries can be recharged or replaced at any required speed can be reliably predicted, then the energy stored on the on-board electrical storage system can be managed in an optimal manner in any desired respect [LS05].

In our study we obviously consider only rechargeable batteries whose important characteristics are energy capacity, years of service life, load characteristics, safety, price, self-discharge, environmental issues, maintenance requirements and disposal. Out of these characteristics four parameters are important for modeling an AEV: the energy/weight ratio, the energy/volume ratio, the power to weight ratio and the cost in watt-hours per dollar.

Although from day to day the properties of existing batteries improve, as new types of batteries are invented, we give below a brief summary of their main characteristics starting with Tables 1 and 2.

A successful energy storage system for electric vehicles commonly needs to achieve increased vehicle performance, extended storage system service life, improved cold weather performance and reduced storage system volume or weight. Such systems are usually hybrid consisting of arbitrary combinations of various types of batteries and ultra-capacitors [PCKW10, ABAW10]. The later, store more energy than conventional capacitors by using a substrate with two porous layers separated by an extremely thin layer of insulation. They are larger than batteries and store relatively less energy but offer ex-

³<http://www.gridlabd.org/>

Type	Chemistry	C-rate ⁴	Time	Temperatures
Slow charger	NiCd, Lead acid	0.1C	14h	0-45C
Rapid charger	NiCd, NiMH, Li-ion	0.3-0.5C	3-6h	10-45C
Fast charger	NiCd, NiMH, Li-ion	1C	1h+	10-45C
Ultra-fast charger	Li-ion, NiCd, NiMH	1-10C	10-60'	10-45C

Table 2: Characteristics of each battery for the four types of chargers [http://batteryuniversity.com/learn/article/all_about_chargers]

Figure 1: The hybrid energy storage system considered.

tremely high power delivery. Furthermore, ultracapacitors are very robust and tolerant of mechanical vibrations and cold temperatures, may be charged and discharged more than 500,000 times, and last longer than 10 years.

For our study and in general to power the electric propulsion system of vehicles with relatively short range it is proposed [Mik10] that a suitable effective electric energy storage system uses batteries and ultra-capacitors configured as shown in figure 1 where allocating electric drive at each axle allows for maximum energy recovery from regenerative braking.

The thematic area of modern energy storage systems and in particular the new types of batteries is not the only one that exhibits significant technological and scientific results concerning AEVs. The area of renewable

energy sources in general and solar and wind in particular is another one. In fact, to switch our electricity generation to renewable sources, we need have to add smartness to our electric grid and to store electricity when there is oversupply. Specifically, when a renewable source generates energy, it's not necessarily when it is actually needed and therefore needs to be stored. Unless, these sources generate power for a system that consumes it at a mostly predefined or at least easily predictive pattern. We claim that such system is the AETs we consider in this study. We focus on the two widely available renewable sources the sun and the wind and we briefly review the associated technologies below.

Solar panels are devices that efficiently convert sunlight to electricity and are commonly classified as monocrystalline, polycrystalline or amorphous silicon [SW06]???. They are constructed by joining together smaller solar cells which absorb the photons (the energy particles contained in the sunlight) into the panel's semiconductor material. The photons dislodge some of the electrons and as this disruption continues, the electrons begin to migrate toward the upper part of the solar cell generating the electric current in a solar panel.

Wind turbines are devices that convert kinetic energy into mechanical energy which is then converted into electricity. We can distinguish two types of wind turbines, horizontal and vertical axis. The former, and the most common, has both the motor and the generator at the top of the construction. Its disadvantage is that in order to be effective it must be pointed to the wind. The latter has the motor arranged vertically and it comes without the previous drawback. It should be noticed that economic wind generators require windspeed of 16 km/h or greater.

For the rest of this paper we concentrate on *simulation of trains* that

- are not directly connected to the electric power system,
- rely solely on solar and wind energy systems as well as acceleration and regenerative braking,
- use the electric power distribution system to charge the batteries only in extreme/emergency cases,
- run on relatively short regional routes,
- is environmentally friendly producing minimal amount of CO_2 and

- are of low development and operational cost.

3 Related efforts

To the best of our knowledge no other studies have appeared in the literature that aggregate all electric trains with renewable energy sources located at selective stations on their routes. Furthermore, it appears that there exist only a few recent efforts that related to some the specific objectives of our study as those were described in the previous sections. Below we briefly review almost all of them. It is important to mention here that for each one of the efforts described here we were able to find very little (in some none) significant technical information.

The general idea of trains similar to the ones considered in this study first appeared almost a century ago in commercial trains. The historically first one was in Cuba [hav13] which actually never became fully operational. At the same time other special purpose all-battery locomotives appeared but the motivation was completely unrelated to ours. They were, a few are still operational, utility and construction locomotives used in mines or underground transportation systems like the Metronet in UK.

The first one was launched in 1990 and it is related to the so called SolTrain project in U.S.A.. According to its official web page⁵ the SolTrain was supposed to be propelled in-built batteries and electric motors, and be consisted of a regenerative braking system. No technical details were available. Manufactured Soltrains were expected to be available in 2004 but it seems that the project has been abandoned.

Another early project, a collaboration of the University of Leon and the state-owned railway company Feve in Spain, aims to designed an electric train that operates with solar energy through distributed photovoltaic panels that captured energy to the batteries. This train is known as *Robla Solar* ⁶. It seems that this project is also abandoned.

Additionally, it is worth to be mentioned the locomotive of the Urban Solar Train at Swiss ⁷ which is driven by the on-board 2x20 kW, 96V, 1'000 A battery sets (it is not clear the way of battery's charging.). The train has

⁵<http://www.soltrain.itgo.com/>

⁶<http://www.informacioncursos.com/energia-solar/tecnologa-verde-tren-solar/>

⁷<http://www.swissroadtrains.ch/urban-solar-train>

constant speed 20 *km/h*, 12,000 *kg* weight and consists of two wagons which have Ertex Solar panels, 142.5 Wp each of them, on the roof. These panels collect the required energy that is needed in order to operate systems such as air conditioning and lights. It has battery autonomy of 5 hours on route with and without gradient.

The most comprehensive and advanced effort is the Norfolk Southern's Co No. 999 train (shown in Figure 2), a collaboration effort between US department of Energy, the Federal Railroad Administration and the Pennsylvania University. It was publicly presented in 2009 and it is considered as the first all-electric, battery-powered locomotive in the United States. This 1,500 horsepower train is powered exclusively by a lead-acid energy storage system comprised of 1,080 12-volt batteries to operate in railroad switching applications without the use of a diesel engine. It can regenerate the braking energy as well.

Figure 2: The Norfolk Southern's No. 999, all-electric, battery-powered locomotive.

It is worth to also mention that a multidisciplinary Eller/Univeristy of Arizona team plans to develop and test a conceptual, 220mph all electric train between Tucson and Phoenix⁸. It will consume 110 megawats which will be generated by overhead solar panels mounted above tracks as artistically depicted in figure 3.

In any case, little research has been conducted on the optimization of railway system infrastructure by incorporating Energy Storage Systems (see [LLPGM⁺12] and references therein). Such systems are considered as one of the main driv-

ing forces for improving railway electrical systems in general.

The direct utilization of photovoltaic panels to power electric trains is in fact a recent concept. An effort to prove this concept is a train in Belgium with the capacity of running on solar energy. It involves 16,000 solar panels on the two-mile long roof of a rail tunnel, on the route between Paris and

⁸<http://www.solarbullet.org/>

Figure 3: Merging solar power at utility scale with very high speed rail. The SolarBullet concept (illustration). [Curtesy of www.solarbullet.org]

Amsterdam and expected to expand soon ⁹. In a rather similar manner a project associated with a newly completed Hongqiao Station (on the Beijing-Shanghai High-Speed Railway line) promise even more. It consists of 20,000 solar panels that cover a roof area of 61,000 sq m and have produced 300,000 kwh power since the 160 million-yuan project began very recently ¹⁰.

Finally it is worth to mention here that a comprehensive design and evaluation study concerning the design and the evaluation of hybrid energy storage systems for electric trains can be found [Mik10], where several of the many technological innovations possible with electric power trains are presented.

4 Implementation

To effectively develop a simulation system, as the one described above, it is very desirable (if not necessary) to rely on a general purpose, robust and powerful simulation environment for electrical energy systems. This allows us, by reusing their runtime environment, their core components and the plethora of their third party add-ons, to rapidly develop our system in the most effective and appropriate way. These systems commonly focus on the study and analysis of the behaviour of existing or envisioned power energy

⁹<http://cleantechnica.com/2010/10/23/>

¹⁰<http://cleantechnica.com/2010/07/20/>

systems. More specifically they provide tools for the following issues, which in fact are crucial for the present study

- long-term energy production and distribution design,
- short-term simulations of operations,
- market design and analysis.

The basic elements that can be modeled with these systems are the power flow, the short-circuits, the system's stability and the optimum power distribution and delivery.

There exist several such general purpose energy simulation systems with diverse characteristics focusing on equally diverging objectives like preliminary feasibility studies and general dimensioning, economic and marketing considerations, detailed technical configurations, system analysis or detailed research studies. Some of them are commercial (e.g. INSEL and TRNSYS) few are freely available (e.g. openmodelica), while some are build on top of more general purpose systems (e.g. VisSim and MATLAB/Simulink with the associated toolboxes like the PV Toolbox and the Wind Turbine Blockset. For an excellent up-to-date review of the available other related simulation tools the reader is referred to [MDNG11] and the references therein.

For the purpose of our study we have reviewed the above mentioned systems (as well as several others like Simpow¹¹, InterPSS¹² and Neplan¹³) and we have selected GridLAB-D [CSG08], a recently developed system that is freely available, is object-oriented and it provides the analysis capabilities needed to study the interactions of the various components and mechanisms involved in our simulations in almost real time during long time periods. Furthermore, GridLAB-D can determine the simultaneous state of independent devices, each of which is described by multiple differential equations solved only locally for state and time and it is easy to integrate with new modules and third-party systems.

In more detail, GridLAB-D is developed by Pacific Northwest National Laboratory in collaboration with industry and academia with support from Department of Energy Office of Electricity Delivery and Energy Reliability.

¹¹<http://www.stri.se/metadot>

¹²<http://community.interpss.org>

¹³<http://www.stri.se/index.pl?iid=4255>

It is an agent-based simulation environment that allows us to add or extract our own modules.

GridLAB-D uses glm (GridLAB-D model) files for modeling and simulating power grids. A GridLAB-D model may have either the form of a glm or an xml file that contains specifications for the synthesis of multiple objects in order to create a simulation model. **Glm files** are used for model simulation while **xml files** are the communication files between GridLAB-D and third-party systems

For the implementation of our simulation engine we have utilized the GridLAB-D modules **tape**, **power flow**, **climate** and **residential** and we have extend the **generators** module by adding two more classes. These classes model the charge-discharge of batteries and the energy consumption between the stations of a route. To achieve our purpose we use two glm files. Each file focus on different points. The first calculates only the energy consumption so it uses the object `energy_consumption` from the corresponding class. The second one simulates the discharge of battery and it is also responsible for the configuration of pv panels and wind turbines that are used to the simulation model. Below are given more information concerning the various components involved and the reader is referred to the GridLAB-D's primary for all the technical details.

The **tape** module implements objects that can be used to establish and change the boundary condition on a model. It observes the properties of individual objects or the aggregate properties of a group of objects. **Player** and **shaper** objects are used for updating the model at specified times from a file. **Recorder** and **collector** objects are used for collecting information from the model.

The **residential** simulates single-family homes with various appliances, electronics, and occupants. We use it in order to take the energy consumption of lights and A/C which have same characteristics like the trains.

The **climate** module provides an interface that other objects may use to include weather data in their calculations. Objects such as houses and buildings rely on this data to factor outdoor weather into their calculations for internal temperature. The climate data includes temperature, humidity, and solar radiation which is used to calculate temperature gain that is the result of heat gained from direct exposure of a surface to sunlight and wind speed as well.

The **generators** module , or DG, model within GridLAB-D has not been fully developed yet. Instead, the goal of GridLAB-D team is to create the

basis of an environment that the users can extend to create their own models. We have extended this module by adding the additional classes `solar_train` and `energy_consumption`. We also use the object `solar` of this module in order to take the radiation and calculate the solar energy which we use to charge our batteries at the stations.

The general model of our platform is displayed in figure 4. As it can be observed there are three main interdependent internal to GridLAB-D components. The first one is associated with sources: photovoltaic panels, wind turbines, regenerative braking system and the network load. We have not implemented the later, assuming that our ultimate objective is to run completely independent from the power grid at least at this stage of the study. The second component consists out energy storage system. Here it is worth to mention that the energy produced by the regenerative braking system is commonly stored chemically in a bank of capacitors or in the batteries. So, there is minimal energy losses. In our case we only utilized batteries leaving the implementation of capacitors, especially ultra-capacitors aside until an associated module will be available in GridLAB-D. The battery discharges mainly due to elevation, the motion of wheels, the lights and the A/C.

According to figure 5 in the summer the demanded energy can mostly covered by solar while in the winter by the wind. In order to take the weather, especially the radiation and the wind speed, tmy file (component of climate module) is using which has encoded the weather. So, using the data that hellenic national meteorologic service offers we create the corresponding file which contains the radiation, elevation and wind speed for the considered route.

The class that calculates the energy consumption, and therefore the batteries discharge, is of obvious importance since it determines the on board battery replacement. Of equal importance is of the class that calculates the off-board charge of the batteries which depends besides energy source characteristics on real-time weather data as well.

To develop our model for the train's battery discharge we consider the following four resistances that are responsible for the train's energy consumption

F_L Total aerodynamic resistance,

F_R Total rolling resistance,

F_S Gradient resistance and

Figure 4: The component facet of the architecture of the proposed and simulation platform.

Figure 5: Total Cloud Cover (image on the left) and Surface Wind Maps (image on the right)

F_N Curve resistance.

Using Newton's 2nd law, we derive [LS05] the following equation concerning all the above resistances and train's motion

$$m_{tot} * a = F_M - F_R - F_S - F_L \Rightarrow F_M = F_R + F_S + F_L + m_{tot} * a. \quad (1)$$

where

- m is the train total weight in kg
- a is the acceleration of train

Aerodynamic and rolling resistance dependent on a plethora of factors. The former dependent on the frontal area of the train, its speed and shape while atmospheric factors as air density and wind direction have also effect on the value of aerodynamic resistance.

$$F_L = 0.5 * \rho * C_l * A_{fr} * (v + v_{wind})^2 \quad (2)$$

where

- v is the train's speed in m/s
- v_{wind} is the (head) wind speed in m/s
- ρ is the air density in kg/m^3
- C_l is the drag coefficient
- A_{fr} is the frontal area in m^2 , often assumed to be $10m^2$

The function of rolling resistance is the above

$$F_R = C_R * m_{tot} * g \quad (3)$$

where

- C_R is the rolling resistance coefficient
- m_{tot} is the train total weight in kg
- g is the acceleration of gravity

The gradient resistance depends on the weight of the train and the size of the gradient if the train doesn't move on flat straight stretches.

$$F_S = m_{tot} * g * e(t) \quad (4)$$

where $e(t)$ is the elevation as a function of the particular time instance t .

Summarizing, the battery discharge can be expressed with the following, recursive with respect to time, function

$$\begin{aligned} f(t) = f(t-1) & - (0.5 * C_l * A_{fr} * (v + v_{wind})^2 \\ & + C_R * m_{tot} * g + m_{tot} * g * e(t)/1000 + m_{tot} * a). \end{aligned} \quad (5)$$

In order to assist the user to provide values from the above described parameters we have developed a *Graphical User Interface (GUI)* which is depicted in Figure 6.

As seen the user may enter the various parameters of the model to be simulated which they want to simulate. These are the train's weight and speed, the number of passengers, the type and the energy capacity of the battery, the number of stations and their position along the route. Other data are provided through files that either contain static data (e.g. elevation and statistical climate data) obtained through the system's databases or dynamic data (e.g. like weather data obtained through web services in almost real-time). The above data are associated with the external to GridLAB-D components depicted by the icons on the right part in Figure 4.

The user may then start the simulation and monitor its execution over the web while the produced data are presumably stored in the system's database creating a valuable knowledge base system. The GUI is connected to the GridLAB-D part through, glm files, Mex code and matlab scripts.

In summary:

- The user
 - configures the glm file that is responsible for the discharge of battery (object solar_train) by defining the essential characteristics of the renewable resources (PV panels and wind-turbines) available. She very rarely needs to modify the other glm file that calculates the energy consumption between the stations (object energy_consumption).

Figure 6: The functional facet of the developed simulation system.

- enters train configuration related parameters through the GUI. For simplicity in our engine presentation we have been assigned fixed values to certain such parameters (e.g. each for our pilot implementation we assume four engines, 174KW each). These parameters may be also exported to the GUI if needed.
- The Matlab invokes the executable of GridLAB-D, which is at the same folder of the script, by using the command `!gridlabd filename.glm` and executes, (by using MEX code to access data of GridLab-D, the two glm in particular)
 - first the glm file which is associated with the energy consumption and produces the associated data.
 - the glm file which is responsible for the battery discharge by feeding it with the above produced data.
- Stores the output data to our database (or other means, e.g. excel files) and present them graphically through the GUI.

5 Simulation

In this section we present selective experimental results obtained through our simulation system on two real life scenarios associated with peripheral train routes in area of Volos in central Greece.

where and the average wind speed is above 15km/s for 7 months and compliment sunlight

GridLAB-D currently provides three available categories of photovoltaic panels:

- monocrystalline,
- polycrystalline,
- amorphous and
- thin film and concentrator that are not available yet

We have used single crystal silicon panels due to their efficiency, a range between 11 to 19% compared with amorphous silicon and multi crystal silicon panels that have 6 to 8% and 11 to 16% respectively. We prefer using single crystal silicon because of its high efficiency and its range of 135-170 Watts per m^2 instead of 120-150 and 60-80 Watts per m^2 which offers polucrystalline and amorphous respectively. Also, amorphous pv system needs 2-3 times more panels to produce the same output as crystalline. Thin films are better than monocrystalline, instead of the low efficiency which is its main disadvantage, because it is easier to handle them and it is not so susceptible to damage. However, they are not available, so we use monocrystalline.

GridLAB-D provides four different types of commercial scale wind turbines. *GENERIC_SYNCH*, *GENERIC_IND*, *VESTAS_V82* and *GE_25MW*, the selection of which is close correlated with the goals we have to achieve. To be more specific, *GENERIC_SYNCH*, and *GENERIC_IND* have maximum power production of 1.5 MW, turbine height of 90 meters and blade diameter of 82.5 meters. *VESTAS_V82* has 1.65 MW of maximum power production, 78 meters turbine height and 82 meters blade diameter. Finally, *GE_25MW* has 2.5 MW, 100 meters and 100 meters respectively. So we choose *VESTAS_V82* wind turbine due to the minimum required area and the acceptable amount of power supply that provides.

Figure 7: The elevation data for the for the Volos - Larisa (top figure) and the Lechonia - Milies (bottom figure) routes.

We have selected two local operational train routes that both have particular common characteristics although they drastically differ otherwise. Specifically, we have considered

- R1** The regional Volos-Larisa-Volos train. The schedule and stations information is given in figure 11 while the particular train route (see Figure 8(top)) and the elevation information is provided on the left in Figure 7(top).
- R2** The historical Pelion light train¹⁴. The particular train route (see Figure 8(bottom)) and the elevation information is provided on the right in Figure 7(bottom).

As regards the way that the batteries are charging, we mention that pv panels are charge of it. Each month the energy that pv panels provide is different. Also, the area of pv panels is a factor that effects the efficiency and the total energy. Figure 9 represents the energy that is given by pv panels for the whole year and for 4 different cases of pv panel area. The radiation ¹⁵

¹⁴http://en.wikipedia.org/wiki/Pelion_railway

¹⁵Ministry of Environment and Climate change *

Figure 8: Map exhibiting the route and the rail-stations for the Volos - Larisa (top figure) and the Lechonia - Milies (bottom figure) cases.

per month at meteorological stations New Agchialos and Larisa is represented in Figure ???. We suppose for Volos and Lechonia - Milies region that the radiation is the same as the New Agchialos one because of the same latitude and longitude. In order to calculate the energy that a photovoltaic system offers, we use the object solar from generators module of GridLAB-D which has as properties the *type*, *efficiency*, the *area* of pv panel. In Figure 9 is represented the energy per month that pv panels offer for both routes.

The above discussion is graphically summarized in Figure ???. We should mention here that the photovoltaic systems may conveniently be place either at the two terminal stations, Volos or/and Larisa for one case and Lechonia or/and Milies. Also, photovoltaic systems can be placed at any other stations as it is the case in many other European train stations. Figure 10 displays the way that pv panels can be settled at the intermediate stations (left figure) or the terminal station(right figure).

Wind energy may also be used to charge our batteries. It seems that the area where our simulation cases considered is also suitable for small or medium size wind power instalments [Kal11] with annual mean wind speed of $3.2m/s$.

The data shown in Figure 13 are associated with the route characteristics of Volos-Larisa train.

After plethora of experiments in order to verify the soundness of our platform we concluded that the operation of a train which motion is depended only to batteries is feasible. In this paper we present two case studies one for the Volos-Larisa train and one for the Lechonia-Milies train. For the first case study the characteristics of the simulation model represented in Table 3 for the battery characteristics and in Table 4 for the configuration of the train. Figure 12 displays the way that a 200kWh and 100kWh battery is discharging during the route Volos-Larisa and Figure 12(down) for the Lechonia-Milies route. The charecteristics of battery for the Lechonia-Milies case is the same as the Volos-Larisa and the configuration of the train represented in the third column in Table 4. It's worth to note that in case of 100 kWh battery it is necessary the change of battery at the station that our simulation engine decides this decision.

Figure 13 represent the number of routes that can be carried out each day. It is observed that even the winter season, it is feasible the accomplishment of satisfied routes in the case of Volos-Larisa route.

Figure 9: The amount of the mean solar energy produced per day by 500, 1000, 2000 and 4000 m^2 solar panels for Volos-Larisa route(top figure) and Lechonia-Milies route(bottom figure)₂₃

Figure 10: Common placements of photovoltaic panels at intermediate stations (image on left) or terminal stations (image on right).

TRAIN	1571	1573	1575	1598	1577	1579	2594	2571	2573	2575	2577
ΒΟΛΟΣ	5.30	7.30	10.25	...	12.25	15.25	...	17.25	19.25	21.25	23.25
Μελισσιάτικα	5.36	7.36	10.31	...	12.31	15.31	...	17.31	19.31	21.31	23.31
Βελεστίνο	5.46	7.46	10.41	...	12.41	15.41	...	17.41	19.41	21.41	23.41
Στεφανοβίκειο	5.53	7.53	10.48	...	12.48	15.48	...	17.48	19.48	21.48	23.48
Αρμένιο	5.56	7.56	10.51	...	12.51	15.51	...	17.51	19.51	21.51	23.51
Κυψέλη	6.01	8.01	10.56	...	12.56	15.56	...	17.56	19.56	21.56	23.56
ΛΑΡΙΣΑ	6.18	8.18	11.13	7	13.13	16.13	7	18.13	20.13	22.13	0.13

Figure 11: The route, the timetable and the stations for Volos-Larisa train

Battery Characteristics	
Type	Li-ion
Capacity	200KWh
Efficient	85%
SoD	25% of battery's capacity

Table 3: Battery characteristics for both Volos-Larisa route and Lechonia-Milies route

	Volos-Larisa	Lechonia-Milies
Weight	44 tones	20 tones
Passengers	70	50
Speed	100 km/h	20km/h
Power	4*(174kw)	4*(174kw)

Table 4: Existing train configurations for the Volos-Larisa and Lechonia-Milies routes

Figure 12: Battery discharging of Volos-Larisa (top figure) and Lechonia-Milies (bottom figure) routes.

Figure 13: Number of routes per day 200 kWh battery and for the Volos-Larisa train(top figure) and Lechonia-Milies train(bottom figure) WE NEED TO REDO THIS??

6 Conclusion and Future Studies

In this study we consider a simple and practical concept concerning medium size AEVs on fixed routes that offers several advantages. To effectively design a system like the one considered in this study one has essentially to either develop a perhaps physical prototype or express this system as a rather complex multi-objective optimization problem whose solution is a challenging numerical problem.

Considering both the above approaches to a large extent unnecessarily complicated, time consuming and expensive, we design and implement an associated simulation engine for proving our concept and for elucidating its main characteristics considering the case of existing and operational train configurations. Our preliminary simulation data suggest that the operation of a AET that consumes energy from renewable sources only, is feasible and to some extent practically and most probably financially attractive. In particular, in cases with certain characteristics, like routes with no strong elevation variant, such trains might consist the most appropriate practical solution even with existing technologies and under certain financial restrictions. In any case, a further and deeper techno-economic feasibility analysis study is surely required.

Our simulation results are restricted on electric trains of small and medium sizes and routes. Nevertheless, our methodology and the simulation engine developed can be very easily applied, to any kind of vehicles with fixed routes or with routes whose data are available on-line at almost real time. The experimentation in this direction is under way together with minimal system extensions and comprehensive analysis. Therefore, our present paper could be considered as a preliminary study of a broader effort in the area of the electric vehicle routing.

Finally, we should clearly state that our study is by no means complete. We have overlook several important issues that are, to our believe, orthogonal to our current study and do not affect the practical and the scientific merit of our effort. For example, it is still unclear how to control large EV battery systems. As we move from the family-size EV to mid- or large-size ones, our battery systems will probably not consist of just large collections of small batteries. Such systems are expected to suffer from temperature control problems as well as from serious charge estimation issues. It is expected that they will be replaced with systems compromised of larger next generation batteries [SW06] which technologically will drastically differ from the existing

ones.

Gridlab-D platform is rapidly penetrating the large scale electric simulation area and constantly increasing its user's and contributor's communities. The fact that our simulation platform is primarily an extension of Gridlab-D allows us to greatly benefit from its success. For example, it is surely reasonable to attempt to extend our simulation engine with a self-regulating distribution system associated with our renewable energy sources. A task that may follow the findings of [WWCD13] where the associated platform is also based on Gridlab-D. Another reasonable addition to our system will be a runtime Graphical User Interface (GUI) that will allow not only system designers and evaluators but also actual operators that need to react in almost realtime. Again such an extension could be directly based on the approach used in [SGC12] to develop a series of GUIs for GridLAB-D. Our future plans also could include the import of CSV Reader to our model, component of GridLAB-D, which allows a user to import their own weather data. In our case through CSV reader the temperature, the wind speed, the solar radiation and the elevation can be imported.

Finally, we should mention that all software developed in this study is available (under an Attribution-NonCommercial 3.0 Unported, Creative Commons licence) online ¹⁶ ready to be forked.

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¹⁶https://github.com/project-hephaestus/full_electric_train

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