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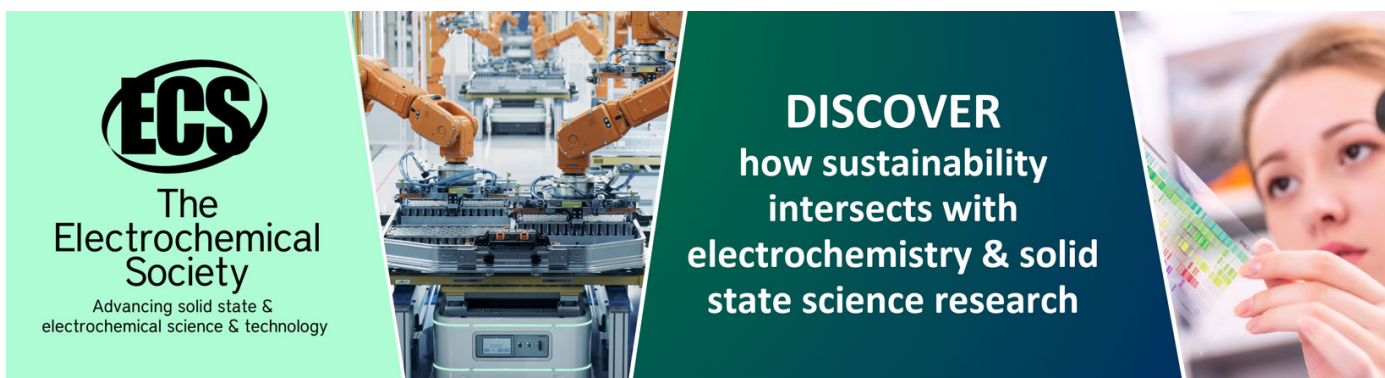
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To cite this article: N Voropai *et al* 2018 *IOP Conf. Ser.: Earth Environ. Sci.* **188** 012016

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Load management possibilities of electric vehicles when expansion planning of electric power systems

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Abstract. Electrical load management is undoubtedly an integral and paramount component of power industry functioning. Electric and hydrogen vehicles are not an exotic vehicle today and the most perspective for solving this problem. The paper studies the impact of advanced environmentally compatible vehicles on electric power system expansion. The potential of their use as load-controlled consumers is assessed. The results of study in the area of electric power system expansion optimization considering this potential for electricity consumption control are presented.

1. Introduction

The ecological, social and economic crises regularly occurring in different parts of the world [1], as well as the ever clearly manifested possibility of depletion of liquid and gaseous hydrocarbons as a fuel for internal combustion engines (ICE) trigger rise of their shortage.

Electric vehicles are the most perspective transport for solving this problem and not an exotic vehicle today. They are universal from the standpoint of utilization of energy resources, as far as they can consume electric energy produced from conversion of the primary energy of coal, gas, sun, wind, water, etc. The use of electric vehicles improves the environmental situation, lowers the noise level, and also allows release of an essential space occupied by the refueling stations, fuel storages and other infrastructure supporting traditional types of transport [2].

However, it is not taken into consideration that the electric energy is produced at ordinary power plants with strict engineering limitations on the operation conditions, fuel and available capacity [3]. Increase in electricity consumption due to the large-scale use of electric vehicles can have an unexpectedly heavy influence on the power industry and call for substantial change in the structure and specification of generating capacities. Nowadays the total power of the world fleet of motor vehicles considerably exceeds the total capacity of operating power plants [4]. Therefore, the mass switch to electric vehicles can provoke power shortage for simultaneous charging of their batteries. This fact determines the need for studying power industry development in terms of the formation of a new class of electricity consumers and elaboration of the concept of its effective integration into the existing structure of electricity consumption.

2. Electric and hydrogen vehicles as perspective types of transport

Until late the lack of appropriate (cheap, reliable, capacious and environmentally compatible) batteries has hampered development of electric vehicles. The sulfuric-acid batteries are bulk and hence, decrease the effective load of electric vehicles. Increase in the volumes of their manufacture and



further utilization, in turn, enhances the ecological burden on the environment. The dry acid-free batteries are expensive and therefore, the electric vehicle becomes noncompetitive against the traditional vehicle. In addition, even after appearance of the batteries with fair average daily indicators of the vehicle mileage (two hundred kilometers and more), the problem of shortage of energy for heating and feeding the auxiliaries still remained. This disadvantage sharply decreased the number of potential customers and made the electric vehicle operation impossible even in the temperature climate.

The following two factors allowed the electric vehicles to pull ahead faster than it was expected by the experts. First, it becomes more and more difficult for the vehicle manufactures to handle regulation of acid dioxide exhausts: the standards in this category become more and more severe in such major markets as China and Europe. And the automotive industry is not ready to follow the standards which can be introduced by these regions by the year 2025. Second, in the years to come the cost of batteries for electric vehicles will continue to decline owing to new developments. The analysts calculated that by the year 2020 the cost of electric vehicles in Europe would be the same as the cost of ordinary vehicles. The electric vehicles will cease to be the vehicles for wealthy customers, who care for the ecology, and become available for general population [5].

For example, a visible progress in manufacture of lithium-ion, nickel-metal hydrid and air-zinc batteries has been observed quite recently making it possible to design competitive prototypes of electric vehicles. Today there are also advanced developments of batteries based on the polypropylene and supercapacitors (ionistors). The problem of heating is also solved by development of different models of special storage heaters that maintain a comfort temperature in the vehicle interior for several hours without charging [6,7].

On the whole, the stock electric vehicles of the nearest future is the direct version of the present-day vehicle, i.e. the convenient vehicle with an average engine power of about 50 kW and a price as from \$15 thousand, i.e. a specific power cost of about \$0.3 thousand/kW.

Such factors as the level of fuel prices for internal combustion engines and the environmental situation in the areas of mass habitation contribute to the mass adoption of electric vehicles. Thus, in the nearest time the electric vehicle can gain recognition and occupy a pronounced part of the motor vehicle fleet.

Another alternative for the vehicle is a hydrogen vehicle with hydrogen as a fuel that is an advanced energy carrier with abundant natural reserves and of high heat capacity which is practically three times higher than that of gasoline. However, the water electrolysis for hydrogen production is an electricity-intensive process that claims careful attention.

The plants for hydrogen and associated oxygen production from water, or electrolyzers, have been in the world practice years ago. In addition, production of 1 m³/h (90 g/h) of hydrogen requires 4 - 5 kW of electric power [8].

The operation safety of hydrogen vehicles that is conditioned by its easy flammability and explosion hazards at its mixing with the ambient oxygen was and is highly questionable. Nevertheless, the latest developments of different motor manufactures in the area of fuel cells on the basis of the cell structure, the use of different self-sealing composite materials and others holds out a hope that the stock hydrogen vehicle will be no more dangerous in operation than the traditional vehicle with ICE.

As a result of works on designing the hydrogen engines the cost of 1 kW of produced power decreased from \$15 to 1.5 thousand over the last ten years, which opens certain prospects of using hydrogen vehicles in the foreseeable future [6].

3. Load management possibilities

The increasing electricity consumption caused by electric and hydrogen vehicles requires an advance search for its provision, primarily by commissioning of new generating capacities. At the same time it should be made possible to order the expected load growth, to make it controllable. In addition, the total electricity consumption is affected by different social and economic factors and therefore, its variations are characterized by a high degree of uncertainty. Apart from the generation shortage probability, there is always the probability that the generating capacities can be underloaded or used

ineffectively. The long-term planning of generating capacity growth subject to load management, in other words the demand-side management, can be a buffer mitigating the consequences of sharp fluctuations in electricity consumption [9].

When determining the extent of load management efficiency its direct contrast to the generating capacity build-up should be evaded, i.e. both these measures should be considered as a reasonable and harmonized complement to each other. For example, from the standpoint of power industry the load management can be advantageous owing to change in the load curve profile, such as by its valley filling and peak shaving. This, in turn, will lead to decrease of the investment and operating costs, fuel saving, efficiency improvement of production facilities and reduction of losses. Consumers have a possibility to save costs on electricity and enhance the control over its consumption. The world community also benefits from the efficient utilization of energy resources, improvement of technologies and abatement of the adverse impact of power generation on the environment [10,11].

The load is managed by means of load-controlled consumers. Physically they can be divided into two basic types:

- special load-controlled consumers subdivided, in turn, into system and industrial;
- average electricity consumers capable of load managing on the basis of available reserves or requiring additional preparation for this purpose (the “average” load-controlled consumers).

The system load-controlled consumers are, as a rule, power system subjects consuming electricity during the off-peak loads and transmitting it back during the peak loads. They include pumped and air storage power plants, storage heaters at nuclear power plants, superconducting inductive energy storages, etc.

The industrial load-controlled consumers use electricity for output of own products during the off-peak hours. They comprise storage heaters of electric heating, electrolysis plants for hydrogen production, electric vehicles, desalination plants, backup electric drive of compressor stations on gas pipelines, agricultural storage electric boilers and electric heaters for hot water supply and heating, facilities for feed preparation and microclimate creation.

Practically any electricity consumer (production, processing line, residential load or individual electric load) may be referred to an “average” load-controlled consumer provided that its full or partial load can be shifted over time without damage to its main activity based this electricity consumption. An additional preparation of the consumer to load management presumes exactly a set of measures on prevention of such damage.

Electricity consumption can be ordered with the help of both the industrial and “average” load-controlled consumers making electric vehicles and electrolysis plants effective. Battery charging and hydrogen production in the night-time hours can fill the night load valleys and prevent increase of its peak values in the daytime. The impact of such load-controlled consumers on power industry development was studied on the Russian example.

The overview of production plans of the leading motor manufacturers shows that the era of electric vehicles has already advanced. Despite the fact that the electric vehicles make up only a slight share of the total market of vehicles as yet, they became an extremely popular innovation. The customers liked electric vehicles so much that in 2017 the largest makers of electric vehicles declared considerable expansion of their manufacture. Manufacture was followed by the high forecasts: Morgan Stanley bank forecasts that by the year 2025 the automotive industry will sell 7 million electric vehicles yearly. The experts of Exane BNP Paribas consider that by the same date the electric vehicles will make up 11% of the total number of vehicles. However, the industry of electric vehicles develops so fast that these forecasts can be out of date soon, in particular, owing to manufacture of the batteries of higher power.

What are the forecasts of manufacturers themselves? The chief executive of the motor company “Ford” Mark Fields considers that the era of electric vehicles is approaching and that in 15 years the number of electric vehicles on the roads will exceed the number of vehicles on combustible fuel. In order to support this optimism the company plans to manufacture 13 new electric vehicles in the next five years. The German company “Volkswagen” has even more scaling plans: it projects to

manufacture 30 new models of electric vehicles by 2025. The American company “Daimler”, the main competitor of the German company “Volkswagen”, also plans to increase the sales of electric vehicles to 1/5 of the total number of soled vehicles [5].

Thus, according to the most modest estimates about 50 million electric vehicles can be manufactured in the world by 2030, which will be equal to about 10 % of the total number of vehicles brought into service (figure 1). The total power of such a fleet of electric vehicles will amount to some 2500 million kW. The Russian share will be about 0.5 million vehicles at a power (a potential of load management) of 25 million kW.

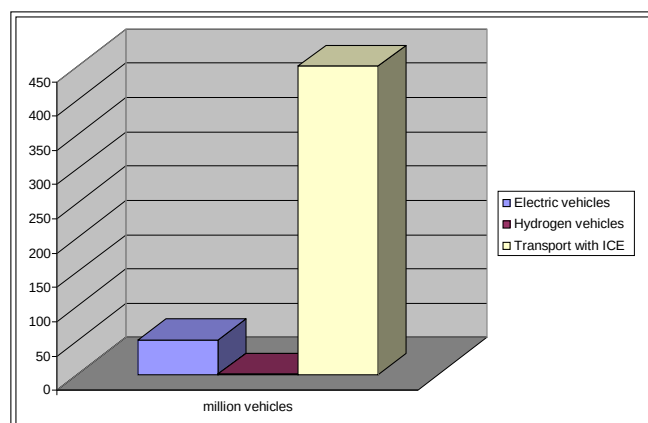


Figure 1. The ratio of advanced types of transport, 2030.

If the fleet of hydrogen vehicles is about 0.1 % of the total number of vehicles, their number can reach the level of 0.05 million vehicles. The traditional transport replaced by such number of hydrogen vehicles would use about 0.5 million liters (0.35 million kg) of liquid fuel daily at the daily average mileage of 100 kilometers and the average fuel consumption of 10 liters per 100 kilometers.

For hydrogen with its heat capacity three times higher than that of liquid fuel its daily use would be 0.12 million kg. Production of such amount of the energy carrier will require 0.57 million kW of power with their operation for seven hours (during the off-peak load).

4. Determination of the optimal scales of using electric and hydrogen vehicles as load-controlled consumers

The impact of electric and hydrogen vehicles on power industry development in Russia was studied on the basis of the mathematical model “SOYUZ” [12,13]. The model comprises the block which describes load-controlled consumers and has some advantages relative to competitive developments:

- a certain flexibility that facilitates modeling of electric power system elements differing in the extent of complexity, relations, methods for accounting diverse factors and criteria of problem solutions, etc.;
- the most complete compliance with the requirements of optimization studies in electric power systems;
- the capability to study effectiveness of electricity consumers in electric power system expansion management.

For adaptation of the initial model to the research problems of electricity consumers for electric power system expansion management it was supplemented with the blocks of mathematical models of electricity consumers. As a result the model can be represented in the following generalized form:

$$\min \sum_{jst} C_{jst} X_{jst} + \sum_{ji} C_{ji}^E X_{ji}^E + \sum_{ji} C_{ji}^H X_{ji}^H + \sum_{ii'} C_{ii'}^E X_{ii'}^E + \sum_{ii'} C_{ii'}^H X_{ii'}^H \quad (1)$$

$$\text{subject to } F(X_{jis\tau}, X_{ji}^{\Sigma}, X_{ji}^n, X_{ii'}^{\Sigma}, X_{ii'}^n) = 0 \quad (2)$$

Expression (1) is the functional minimized subject to constraints (2). In the general case it is represented by the total discounted costs on electric power system expansion and operation, and the studied load-controlled consumers, as well as the energy saving technologies.

Here j is number of the group of uniform generating equipment or electricity consumer; i is number of the node; s is number of the typical daily load curve; τ is index (duration) of the load zone in the daily curve; $X_{jis\tau}$ is daily load s of the j -th type of equipment at node i in the zone of τ hours long or power (load shedding) of load-controlled consumers or energy saving technologies, $C_{jis\tau}$ are corresponding specific variable costs; $X_{ji}^{\Sigma}, X_{ji}^n$ are selected installed capacity and new (commissioned) capacity of the j -th equipment (consumer) at node i ; $C_{ij}^{\Sigma}, C_{ij}^n$ are specific fixed annual costs on and investment in this equipment; $X_{ii'}^{\Sigma}$ is transfer capability of the interconnecting line between nodes i and i' ; $C_{ii'}^{\Sigma}$ are specific annual costs on this line; $X_{ii'}^n$ is transfer capability of the new interconnecting line between nodes i and i' ; $C_{ii'}^n$ are corresponding specific investment.

The first two sums in the objective function determine the annual variable and fixed costs at power plants and modeled consumers, the third sum corresponds to the investment in their creation, the last two sums determine the annual fixed costs on and investment in the interconnecting lines.

Constraints (2) include power balances of the nodes, engineering limitations on the operation conditions of generating equipment and electricity consumers, limitations on fuel, etc.

The annual energy balance of the nodes in the model is described by a set of balances of the zones of representative daily load curves with transition to the annual indices in the model functional through the coefficients of the "equivalent" number of days in a year". For modeling the daily operation conditions the use is made of the "by-zone optimization" principle in accordance with the daily load curve division into horizontal zones of τ hours long which correspond to load increases in different hours of a day:

$$\sum_j X_{jis\tau} + \sum_{i'} X_{ii'\tau} - \sum_i X_{i'i\tau} = P_{i\tau} \quad (3)$$

In expression (3) the first sum represents participation of all power plants of the node, load-controlled consumers and measures on energy saving in provision of the zone of an individual daily curve, the second and third sums are "incoming" and "outgoing" flows between nodes of the power system, and the right-hand side is powers of the daily load curve zones.

In modeling the load-controlled consumer account should be taken of the following points:

- both transfer of average electricity consumers to operation as load-controlled consumers and creation of new load-controlled consumers demand some investment;
- the component of costs on electricity at "consumption" can be taken into consideration not in operating costs of consumers, but at power plants which maintain electric power system operation as a result of optimization;
- the shift of power of the load-controlled consumer from the peak zone of the load curve to the off-peak zone releases part of generating capacities of power plants and this may be represented as "generation" by the load-controlled consumer;
- operation of the load-controlled consumer in the off-peak zone will be treated as "consumption".

Based on the above said, the mathematical model of the load-controlled consumer in the problem of power system expansion optimization can be represented as follows:

$$\sum_{\tau} N_{kS\tau} \leq \beta_{kS} N_k \quad (4)$$

$$N_{kSt} \leq \gamma_k \beta_{kS} N_k \quad (5)$$

$$\beta_{kS} = (1 - g_{kS} - \beta_{kS}^{pem}) \quad (6)$$

$$\sum_{\tau} \tau N_{kS\tau} \leq \eta_k \left(\sum_t N_{kSt} \right) \tau_S^{\max} \quad (7)$$

$$\tau_S^{\max} \sum_t N_{kSt} \leq h_k \beta_{kS} N_k \quad (8)$$

Equations (4) and (5) determine a share participation of power of the k -th load-controlled consumer at “generation” and “consumption”, respectively. Here N_k is power of the load-controlled consumer; $N_{kS\tau}$ is power of “generation” of τ hours long in the S -th day; N_{kSt} is power of “consumption” at hour t of the S -th day; β_{kS} is availability factor of the consumer power (share of the total power of “consumption”) that is determined according to (6). In expression (5) γ_k is ratio between the powers of “generation” and “consumption”.

Equation (4) is the limitation on using the “generation” power of the load-controlled consumer and determines that it cannot exceed physically the total power of all loads subject to the availability factor. Expression (5), in turn, shows that the “consumption” power of the load-controlled consumer cannot also exceed the total power of all loads subject to the availability factor.

Expressions (4) and (5) for load-controlled consumers are supplemented with the equation that takes into account energy of “generation” and “consumption” (7) and the constraint on the average daily number of utilization hours h_k (8).

Equation (7) means that physically the energy of “generation” cannot exceed the energy of “consumption”. Here $\tau_S^{\max}$ is duration of one interval; η_k is efficiency factor that is lower than unity, if the work of the load-controlled consumer is connected with intermediate electricity storage or conversion, for example, batteries in electric vehicles.

Limitation on the consumed power (8) depends on the product output volumes, the working shift duration, etc.

Effectiveness of load-controlled consumers was assessed for the period until 2030. The “competition” among the load-controlled consumers was considered in parallel with their “competition” with the traditional types of generating equipment. The obtained results were compared with the initial optimization variant of electric power system expansion in Russia which did not anticipate the use of load-controlled consumers.

It is established that for the optimal power industry development in Russia the volumes of using electric and hydrogen vehicles as load-controlled consumers make up 3.9 million kW and 0.03 million kW, respectively (figure 2).

Optimization of power industry development in Russia considering the advanced types of electricity-consuming transport allows decrease of the investment by \$2.5 billion and operating costs by \$0.3 billion per year on its development. Due to the losses in electric vehicle batteries and electrochemical generators of hydrogen the fuel consumption increases by 83 thousand tce (tons of coal equivalent) or by \$0.1 billion per year.

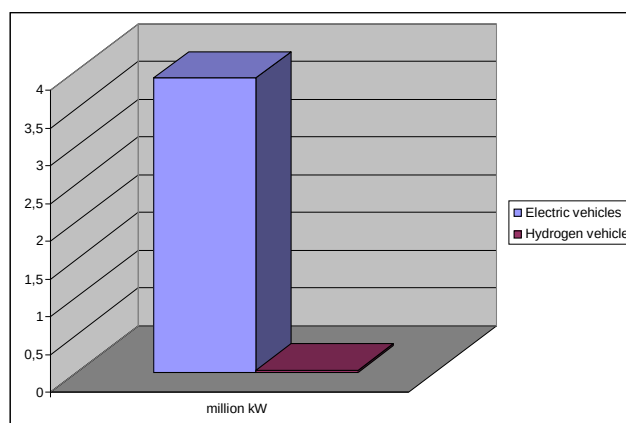


Figure 2. The volumes of using electric and hydrogen vehicles which are optimal for power industry development in Russia.

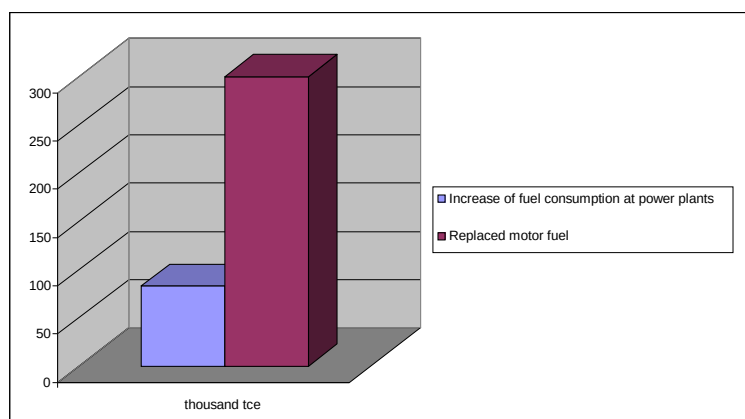


Figure 3. The ratio of increase in fuel consumption at power plants and replaced motor fuel.

The environmental effect of using electric and hydrogen vehicles as load-controlled consumers consist in the decreasing volumes of commissioning peak coal-fired power plants by 1010 million kW, in replacement of motor fuel by about 300 thousand tce per year (figure 3). The main results of the study that were obtained on the example of Russia will presumably be true for the other countries of the world community as well.

5. Conclusion

Application of the advanced types of electricity-consuming transport (electric and hydrogen vehicles) can have an essential impact on electric power system expansion. The relatively low optimal volumes of using electric and hydrogen vehicles as load-controlled consumers are stipulated by the high cost of batteries and electrolysis plants. Their attractiveness will rise with improvement and cheapening of production technologies.

The unregulated modes of charging the electric vehicle batteries and hydrogen production can increase power consumption and degrade total load curves. These facts, in turn, will call for construction of additional generating capacities of power plants with ineffective operation conditions.

At the same time the competent use of electric and hydrogen vehicles as load-controlled consumers with the regular power consumption will eliminate the load curve degradation, improve the structure of generating capacities in the long-term optimization of their evolution and enhance their

performance figures. Moreover, it has a pronounced environmental effect.

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