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Long-term electric vehicles outlook and their potential impact on electric grid

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ABSTRACT

The last decade was marked by a new boom of popularity for electric transport. Massive government support helped increase EV annual sales from just 2 to over 753 thousands worldwide over the ten years. Many countries and private enterprises hold extremely high hopes for electric transport, predicting the imminent abandonment of the internal combustion engines (ICE). Our research shows that in 2018 EVs are yet still unable to compete on equal footing with conventional cars. However, should government and auto manufacturers maintain the current pace of development, true competitiveness between ICE and electric vehicles can be achieved by 2035 even in the low-oil-price environment.

Our calculations indicate that by 2040, depending on the scenario, the EVs can secure an 11–28% share of the global road transport fleet. This will lead to an additional increase in global electricity consumption of 11–20%. The challenge, however, is the adaptation of power grid to the growing demand peaks due to EVs charging patterns. To maintain the course on "green" energy, global leaders in EV adoption need to double the efforts on development and implementation of energy storage technologies, otherwise, the spread of electric cars will lead to more fossil fuel consumption.

1. Introduction

Up until recently the electrical motor seemed to have hopelessly lost the competition as the main method of propulsion for auto transport to the internal combustion engine (ICE) ever since the success of Ford Model T in the late 1910's, which has, pretty much, shaped road transport as we know it today (Matulka, 2014). Yet, the electric drive has never disappeared off the radars entirely as a possible efficient, "green" alternative to fossil fuels. During the infamous oil crisis and embargo of 1970's some of the largest US companies, like Ford, GM and even Exxon Mobil actively looked into electric vehicles (EVs) as a mean to reduce dependence on Middle Eastern oil (Fletcher, 2013). However, a few years of research could not make up for a half a century gap in development with the ICE and, as the situation on the oil market stabilized in the 1980s, the interest towards electric transport faded again.

At the turn of 20th century the issues of global warming and environmental pollution came to the foreground of international politics, prompting an active search for the alternatives for fossil fuels and an eventual resurgence of the EVs. According to OECD/IEA (2017), annual sales of EVs rose from just 2 to over 753 thousands worldwide over the 2005–2016 period, securing a 1.1% share in the global fleet. Such a boom in sales in a relatively short time span can be attributed to large-scale state support of electric road transport by a number of leading economies as well as rapid progress in battery costs and longevity. Combined, these factors increase competitiveness of the EV compared to conventional autos.

At the same time, state-supported hasty expansion of electric fleet may entail not only benefits for the environment, but also a serious challenge for the energy system. Thus, according to Huang et al. (2013), the penetration of EVs may cause a "peak on peak" effect, potentially causing severe grid instabilities, such as those, witnessed in southern Norway in 2017 (Noel et al., 2017)· Similar concerns have been cited by other researchers (Robinson et al., 2013; Spindler, 2014; Schmidt, 2017).

The goal of this study is to provide a scientifically based outlook on the long-term dynamics of EV fleet size, the demand for electricity generated by the said fleet and, consequently, the impact of electric transport development on energy systems of worlds regions. The manuscript contains overview of state and corporate plans and policies concerning electric transport support as well as competitiveness analysis

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of EVs. This data is fed into the forecasting tool, to determine the future of electric road transport, using state-of-the-art modelling approach. Based on the calculations, the impact on energy systems is determined and possible adaptation strategies are formulated.

2. Government and corporate policies on EVs

As of 2018, most of the leading economies support electrification of road transport in one way or another. Moreover, China; Canada; Finland; France; India; Japan; Mexico; Netherlands; Norway and Sweden have joined an international EV30@30 Campaign, with a common goal of 30% electric auto fleet by 2030. Most of the participating countries provide tax incentives for the purchase of electric vehicles; Netherlands, Finland and France additionally provide direct government investments in infrastructure, while Japan introduced tax cuts and preferences to EVs producers (IEA, 2017a).

In addition to EV30@30 members, all of the EU-20 countries along with Brazil and SAR maintain preferential taxation of electric transport. Individual cities, such as Paris and Mexico announced the intent to ban ICE autos from entering city limits. London government does not plan an outright ban on ICE, but introduced fees for using the in-city roads, from which the EVs are going to be exempt (OECD/IEA, 2017) (Fig. 1).

Given the extent of support for the EVs by the developed countries' governments, major auto manufacturers seriously consider a major shift in consumer preferences towards electric transport in their planning. We have analyzed plans and strategies of 12 leading car producers, taking up a total of 78% of the global new car sales in 2017 (Focus2move, 2018) (Fig. 2).

As of 2017, 8 of them have at least one fully electric car in their model range, and Toyota M.C. even boasts a fuel cells car. Moreover, almost all market leaders declare extremely ambitious plans to expand the model line of electric vehicles, and Daimler AG even announced plans for a quarter of the cars produced by the company (which is more than 500 thousand units annually) to have a fully electric drive by 2025.

Naturally, the companies' efforts are not aimed at just expanding the model range of electric vehicles, but also reducing production costs to enhance profitability (Table 1).

Yet, despite all the hype, surrounding electric cars, in the end it is their economic attractiveness for the general consumer that will determine their future. The California case is quite notable in this regard (CA.gov, 2011). In 1990 the state adopted Zero Emission Vehicle (ZEV) Program. The Program required 2% of the vehicles sold in California in 1998 to be ZEVs, increasing to 5% in 2001 and 10% in 2003. Auto manufacturers quickly responded, by introducing emission-free electric cars to their model lines, to a modest success, to say the least. Subsequent easing of the "zero-emission" rule led to the EVs to be almost completely replaced by much cheaper and efficient, albeit not entirely "green" hybrids.

3. Current and prospective competitiveness of electric transport

As of 2018 contemporary electric cars are still inferior to conventional ones over several utility features. Aside from the persisting gap in base purchase cost EVs suffer from limited mileage, long charging times and battery lifetime issues in cold climates (Table 2).

Nevertheless, many consumers are willing to put up with some disadvantages of electric cars, for environmental or fuel efficiency reasons. Moreover, according to ERI RAS estimates (Makarov et al., 2016), in US, Japan and several European countries the combination of tax cuts and other incentives has created a parity of the ownership cost[1] with conventional cars, which led to a surge in sales in 2014–2016.

However, the situation may change in the near future. The key issue to reducing the cost of an electric car is to lower the cost of the battery, which made up half the price of a car in 2016 and this is where all the R&D efforts are concentrated (Soulopoulos, 2017). According to Bloomberg (BNEF, 2019), battery cost will fall by half in 2020 and by 2030–2035 cost competitiveness with no subsidies is to be achieved (Fig. 3).

It is very important to note, that electric transport is not limited to just full-sized cars, but also two- and three-wheeled vehicles, which generate from 5 to over 20% of fuel demand in the transport sectors of such major economies as India, China and Brazil.

This category of electric vehicles is already cost-competitive even sans the government subsidies. The only major downside is the extremely limited mileage, which is not all that relevant; given that these vehicles are predominantly used for short in-city trips (Table 3).

4. Forecast methodology

For the purposes of this study the authors implemented SCANER modelling complex, developed at ERI RAS, which is comprised of an inter-connected web of sophisticated system of state-of-the-art forecasting tools (Fig. 4).

Two modules have been used most extensively over the course of the research: «Forecasting fuel demand in the road transport sector » Module and The Power Industry Module.

The « Forecasting fuel demand in the road transport sector » Module is dedicated to calculating the prospective demand for the key fuel groups taking into account the interfuel competition:

- Liquid fuels – petroleum products and their direct substitutes (biofuels and synthetic fuels), such as: liquefied petroleum gases, gasoline, diesel;
- Electricity, used for powering electro cars, plug-in hybrids, trams, trolleybuses and fuel cell vehicles;
- Natural gas – conventional methane, cleansed from impurities, coal bed methane, or biogas.

Uniqueness of the forecasting system lies in combination of two different approaches to demand forecasting: the «top-down» and «bottom-up » approaches.

The top-down approach consists of conducting regression econometric analysis and predicting future demand for individual energy sources as a function from future values of key macroeconomic parameters (GDP and population) which are set according to scenario in question. Usually, a capacity (ratio) trend of a separate energy source is predicted expressed in energy or natural equivalent in relation to GDP or population. After that, obtained capacity values are multiplied by projected values of GDP and population to receive forecast demand for individual energy sources.

Such an approach is very common for forecasting (Nakanishi, 2006; Kugelevičius and Kuprys, 2007; Chai et al., 2012) as it is fairly easy to implement, mostly due to availability of the source data. However, naturally, it does not permit a qualitative factor analysis, eliminating impact from such factors, as technological development, infrastructure and political agenda. Calculations using the methods of econometric regression analysis are reserved by the authors only to double check the results of «bottom-up » approach for possible critical errors.

Road transport fuel demand forecasts, which utilize the «bottom-up » approach, apply multi-factor models. For example U.S. Department of Energy, IEA, World Energy Council (WEC) make use of this method (IEA, 2011; WEC, 2011; U.S. Department of Energy, 2014), where demand for energy is a function of many parameters, such as the size and structure of the vehicle fleet, fuel and car prices, technological progress, energy policies and others. Taking into account a large number of factors requires input of a lot of data and more complex calculations. This increases the probability of errors in the results either through incorrect data or miscalculations. To avoid these errors, the results are

[1] Cost of ownership – the cumulative cost of purchase, maintenance, fueling etc. of the vehicle in relation to average mileage over its lifetime.

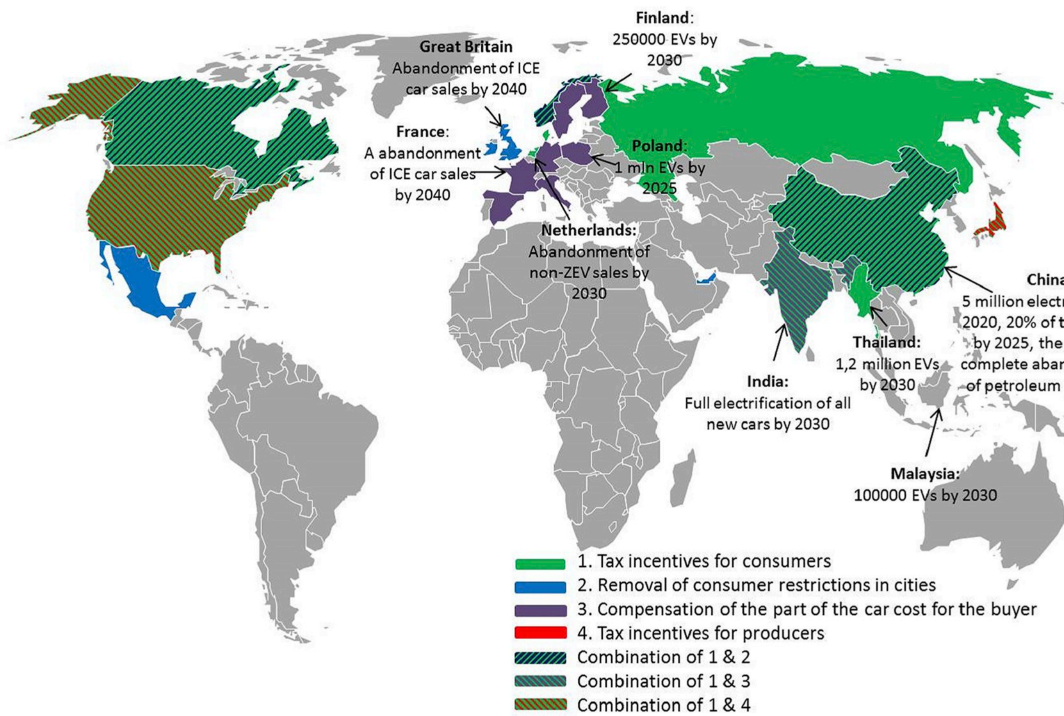

Fig. 1. Electric vehicles state support mechanisms and national goals across the world.
Source: Authors' research

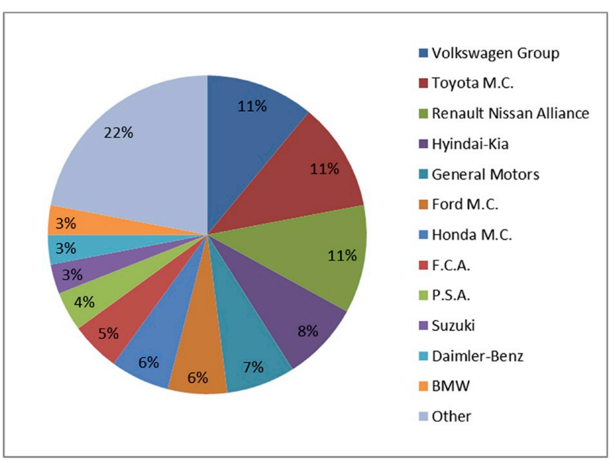

Fig. 2. Global corporate auto sales structure, 2017
Source: Authors' research

cross-referenced with the ones, derived from the «top-down» approach.

The ultimate goal of the forecast system used in this study is to determine demand for each energy source used in the road transport sector. In the «bottom-up» approach it is defined by equation (1):

$$DMF_{t,i} = V_{t,i} \times M_{t,i} \times F_{t,i} \tag{1}$$

t – year;
i – fuel type;
DMF – fuel demand;
V – fleet size by fuel type;
M – vehicle mileage;
F – average net fuel consumption by type.

Vehicle mileage is determined exogenously, based on current average annual mileages of various categories of cars. For the purposes of this study, average mileage data published by national statistical and analytical organizations was used.

Motor fuel consumption by type – average fuel consumption expressed as consumption of the specific energy source per 100 km mileage. Determined based on the average mileage data for the most popular road vehicle types (passenger cars, trucks, light commercial vehicles and two-wheeled vehicles), published on the official websites of car manufacturers and dealers.

Fleet size by motor fuel type is determined on the basis of the following indicators:

The size and structure of the vehicle fleet by fuel type for the base year divided in aforementioned groups; Forecast of the total number of vehicle fleet and individual vehicle types (passenger cars, trucks, light commercial vehicles). To determine this indicator we use the method applied by IEA (2011). This equation method determines the number of vehicles, as an S-shaped function of the saturation level and projected per capita GDP. GDP and population dynamics are set exogenously;

The number of new car sales in a projected year which is determined on the basis of the total number of cars in each subsequent after the base year, and the number of cars disposed of, which is determined on the basis of historical data on annual car disposals.;

The number of new car sales on a particular type of fuel in any given year is calculated according to equation (2):

$$NV_{i,t} = \frac{K_{attractivei,\ i}}{(\sum K_{attractive})} \times \sum NV_t \tag{2}$$

t – year;
i – fuel type;
$NV_{i,t}$ – the number of new car sales on a particular type of fuel;
$K_{attractive,i}$ – attractiveness factor for cars on a particular type of fuel;
$\sum K_{attractive}$ – the sum of attractiveness factors;
$\sum NV_t$ – total new car sales.

When determining the number of new car sales on a particular type

Table 1
The current state of the electric cars segment and plans for its development of the world's major automakers.

Auto manufacturer	Current state of EV fleet	Company's plans regarding electric transport
Volkswagen Group *(Volkswagen; Bentley; Bugatti; Lamborghini; Audi; Skoda; Seat; Scania)*	Two electric car models are present in the company lineup under the Volkswagen brand since 2016. Audi presented a fully-electric SUV in 2017.	The company sets electrification as one of its main strategic objectives. By 2025 30 new models of electric cars are planned for production. The key development area if the substantial reduction of battery cost by 2025 (Volkswagen, 2018).
Toyota Motor Corporation *(Toyota; Lexus; Daihatsu)*	The company's first electric car was released in 1997 as a limited edition for the California market. In 2003, the production was discontinued. From 2008 to 2015, the Toyota IQ electric car was produced, from 2013 - RAV4 EV, a joint development with Tesla Motors, the manufacture of which was also suspended. Currently there are no fully electric cars in the company's lineup, as the focus is on hybrids and fuel cell cars.	By the early 2020s, the company plans to introduce 10 full-fledged electric cars to the market, and by 2030 to sell up to one million electric and hydrogen cars, aiming for a 10% share of the global electric and fuel cell cars market (Greimel, 2017).
Renault-Nissan *(Renault; Nissan; Datsun)*	The first experimental electric car of Nissan concern was released in 1947 and since then the company has not stopped trying to produce a commercially successful electric car, carrying out extensive research in the field of improvement of lithium-ion batteries. Since 2010, the company has a model line of Nissan Leaf, officially recognized as the best-selling electric car in the world.	By 2022, the concern plans to expand the range of electric cars offered to 12 models. The company considers full abandonment of the ICE by 2040 (Lunden, 2017).
Hyundai-Kia *(Hyundai; Kia; Genesis)*	Since 2014, all brands possess one electric car in their model range.	By 2022, the Korean concern plans to develop two electric cars models, one for the premium segment, and the other in the compact class (Voelcker, 2017). By 2035 a commercially viable hydrogen car is planned for production (Jin, 2017).
General Motors *(Baojun; Buick; Cadillac; Chevrolet; GMC; Daewoo; Holden; Isuzu; Wuling)*	The company's first small-scale electric car EV 1 (produced from 1997 to 2003) all vehicles were seized from users and dismantled. Since 2007, the company has restored the production of EVS, at the moment two electric models are in production: Chevrolet Volt and Chevrolet Bolt (General Motors, 2017).	"General Motors believes the future is all-electric", - Mark Reuss, Vice President of the company. By 2023, the company plans to launch the production of 20 electric models, including 2 electric cars in 2018–2019. By 2023 the company hopes to take a 20% niche in the electric cars market (LeBeau, 2017).
Ford Motor Company *(Ford; Lincoln; Mercury; Mazda)*	The first electric car of the company, Ford Ranger EV, was sold under lease agreements in the United States in 1998–2002. By 2003, all contracts were terminated and cars withdrawn. Since 2011, Ford Focus Electric has been produced, the only full-fledged electric car in the company's line.	«Electrifying our next generation of vehicles is core to our unwavering commitment to sustainability», - Joseph Hinrichs, Executive Vice President and President of Global Operations. The company relies on the hybridization of the fleet and the introduction of autonomous cars. The Park of full-fledged electric cars in the next few years is planned to be supplemented with only a single model, which, however, is expected to capture up to 10% of the entire electric car market by 2020.
Honda Motors *(Honda; Acura)*	The company is yet to introduce a fully electric car, however, since 1994 is the leader of the electric motor segment among low-powered two-wheeled vehicles, in particular-fully electric scooters.	The company plans to launch serial production of electric vehicles by 2022, with a focus on ultra-fast charging technology wich should take no more than 15 min (Nikkei, 2017).
Fiat Chrysler Corporation *(Fiat; Chrysler; Dodge; Jeep)*	Microcar Fiat 500e is in production since 2015. In 2017 a hybrid minivan Chrysler Pacifica Hybrid was introduced, capable of functioning as a fully electric car.	In May 2017 the company admitted negative profits of 20 thousand dollars from each electric car sale, thus it does not possess a cohesive strategy for EVs development, instead focusing on autonomous driving (Autovista, 2017).
Peugeot-Citroën PSA *(Peugeot; Opel; Vauxhall; Citroën)*	Since 2011 the company offers two electric models: Citroën C-Zero and Peugeot iOn, which are, however, in fact are just refurbished Mitsubishi i-MiEV.	By 2020, three electric models are planned for production, but the main focus is on plug-in hybrids.
Suzuki Motor Corporation *(Suzuki)*	The company does not offer fully electric cars.	By 2020 the company plans to introduce a fully localized budget EV to the Indian market as a joint project with Toyota and Volkswagen.
Daimler AG *(Maybach; Mercedes-Benz;Smart)*	Since 2007 compact electric cars are sold under Smart brand name. Mercedes B-class EV is in productions since 2015. In 2016 a sub-brand, Mercedes EQ was introduced to produce only electric cars, however, as 2017 the production is dormant.	The company plans to invest up to 10 billion euro into electric transport over the decade to develop 10 models: three under Smart brand; 7 under Mercedes EQ. By 2025 a quarter of all vehicles, produced by the group are planned to be electric (Daimler Investor Relations, 2018).
BMW Group *BMW; MINI; Rolls-Royce)*	A fully-electric BMW i3 is produced since 2013. The company is actively researching into battery lifetime technology along with Korean Samsung.	By 2025 BMW plans to offer up to 12 electric cars, which can be expected to be market leaders in mileage (Preisigner and Taylor, 2017). A luxury fuel cell car project with Toyota is also in development.

Source: Source: Authors' research based on companies' data: Volkswagen (2018); Greimel (2017); Lunden (2017); Voelcker (2017); Jin (2017); LeBeau (2017); Nikkei (2017); Autovista (2017); Daimler Investor Relations (2018); Preisigner and Taylor (2017).

Table 2
Comparison of conventional and electric cars key utility features in 2018.

	Conventional ICE car	Electric car
Cost excluding subsidies, $	**15000-37000**	**35000-45000**
Mileage on one tank/charge, km	**240–710**	**100–580**
Fuelling/charging time, min	**5–10**	**40–600**
0–100 km/h acceleration time, sec	**3–12**	**3–12**
Climate limitations	**None**	**Battery capacities are significantly reduced below -20 ^{0}C**
Service and fueling/charging infrastructure	**Developed**	**Limited**

Source: Authors' research

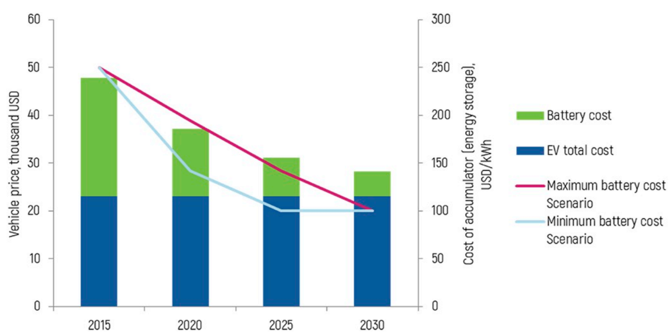

Fig. 3. EV battery cost assumptions.
Source: Authors' research, BNEF (2019).

Table 3
Comparison of conventional and electric scooters key utility features in 2018.

	Scooter	Electric scooter
Cost excluding subsidies, $	**1000–3000**	**1000–3000**
Mileage on one tank/charge, km	**150–250**	**30–100**
Fuelling/charging time, min	**5–10**	**10–360**

Source: Authors' research

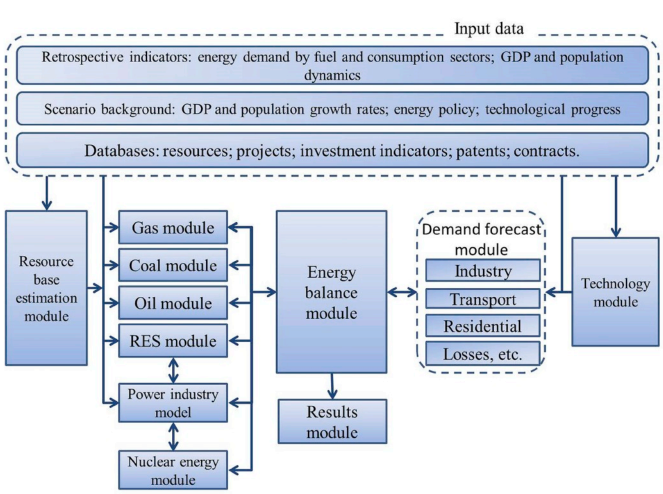

Fig. 4. Flowchart of SCANER modelling complex structure.
Source: Makarov (2011)

of fuel the key parameter, in addition to total sales, is a coefficient of attractiveness of cars on a that fuel type defined by equation (3):

$$K_{attractive,\ i} = K_{opi} \times K_{infi} \times K_{popi} \tag{3}$$

K_{opi} – coefficient indicating the average annual cost of ownership for car utilizing a particular fuel type. It is determined by ranking the ownership costs of car from the cheapest to the most expensive ranging from 0 to 1.

Cost of cars ownership itself takes into account:

1. Price of the average car on the fuel type based on the analysis of prices for the most popular models of car dealers and assumptions about their decline;
2. The service life of the vehicle (determined according to average values);
3. Average specific fuel consumption based on current fuel consumption rates of the most popular cars in the given region and assumptions about the increase in fuel efficiency;
4. Price of the fuel used. For this study retail fuel prices in various regions were determined through the count-conversion factor from the wholesale prices in the scenarios of the Global and Russian Energy Outlook 2019 (Makarov et al., 2019).

K_{infi} – represents the development of infrastructure for the specific fuel type ranging from 0 to 1. Parameters, such as availability of refueling and service infrastructure are estimated, that could impact consumers' preferences for a specific fuel type. Infrastructure coefficients are critical for assessing the attractiveness of vehicles on natural gas, electricity or hydrogen. These factors can also specify different scenarios for construction and development of infrastructure in the different hubs aimed at accessing their impact on demand. Infrastructure coefficient is set at 1 for fuel(s) with best infrastructure, usually them being petroleum products. Coefficients for other fuels are defined as the ratio of the number of fueling stations for the fuel type to the number of the most popular fuel types' fueling stations. Coefficient may be altered empirically to take into account other factors, like the lack of service centers for maintenance of certain equipment in a country.

K_{popi} – rate of consumer preferences for certain fuels reflects the level of convenience for the consumers to use the specific vehicle type, ranging from 0 to 1. This factor encompasses country-based traditions, fashion, government legislations (parking restrictions, special lanes) and other.

The described approach allows for a flexible forecast calculations for the energy demand in the road transport sector identify the influence of individual technological, macroeconomic, or infrastructural factors and assess their impact on the prospects of forming a fuel mix.

To analyze the impact of EV fleet on electricity grid worldwide The Power Industry Module was implemented. The Module is included in the "Free Block" of SCANER and balances the demand for electricity by countries and regions with account for different technologies. The Power Industry Module is a part of the balancing model designed to assess the demand for electricity and energy sources for its production.

The primary task of the block is to balance the electricity demand across all of the reviewed blocks. The secondary task is to determine the demand for coal and natural gas from the thermal power plants with calculation of competitiveness indicators.

Electricity demand by country is the result of a retrospective analysis of electricity demand and the electricity intensity of GDP. The forecast of the structure of electricity production by fuel types is based on the trend analysis:

- the forecast of consumption of oil products in power generation is the result of the extension of trends in their share in the structure of electricity production;

- the volume of renewables (except hydropower) and bioenergy consumption is calculated taking into account the dynamics of their consumption in the electric power industry in relation to the total volume of their consumption, as not all renewable sources and bioenergy are used in the electricity sector. Total amounts of consumption of renewable energy sources and bioenergy is calculated in the balance model;
- the residual demand for electricity is covered by gas and coal in accordance with their changes in shares.

The final demand for each energy source in the power generation is equal to its consumption multiplied by the efficiency of fuel combustion in power plants in the corresponding year. At the same time, assumptions are made about the dynamics of energy efficiency in the power industry. As a result, the electricity balances of countries can be presented in both toe and TW·h.

Since the nuclear power industry is strategic, capital-intensive and is associated with global security, classical market models are not applicable to it. The nuclear module of ERI RAS modelling complex is based on in-depth analysis of energy policies of the countries and analysis of data on each of the existing, under construction and planned nuclear power units in the world.

Thus, the forecast of nuclear energy consumption is based on:

- preparation of historical data on nuclear energy consumption dynamics with the required regional and country breakdown;
- the preparation of a complete list of active, retired, under construction and scheduled for commissioning nuclear power plants around the world, with the date of decommissioning of nuclear power plants;
- determining the dynamics of average annual output of the plant depending on the capacity of the blocks;
- composing medium-term forecast of nuclear energy consumption by countries and regions based on information on each individual unit of nuclear power plants, taking into account new commissions and retirements;
- composing long-term forecast of nuclear energy consumption by countries and regions based on the analysis of national plans for nuclear energy development adjusted for their attainability and expected environmental constraints.

The module of unconventional renewable energy sources aggregates the scenario-specified volumes of renewable energy generation, as well as the additional volumes obtained from the optimization models in the" Summary block ".

Much like in the nuclear module, the forecast of renewable energy is based on the analysis of energy and environmental policies. In addition, the progress of the sector is determined by the development of renewable energy technologies.

The model distinguishes three areas of renewable energy: hydropower; renewables for power generation and heating; renewable fuels for transport. These areas are calculated separately and summarized. The following algorithm is used:

- preparation of statistical information with the required regional and country breakdown for all three areas;
- demand dynamics forecast calculation based on historical trends extrapolation and the method of expert assessment (depending on the specific of the considered countries and regions) based on:
  - o hydropower development potential;
  - o analysis of the national plans and energy policies in the field of renewable energy (given the scenario conditions and assumptions).

5. Scenario assumptions

For the sake of this research two scenarios of EV fleet development have been formulated:

- Baseline scenario, which is a business-as-usual scenario with modest rates of technological development for both ICE and electric vehicles and limited EV support;
- Favorable scenario, which assumes more rapid improvement of electric car technology (mainly battery costs and mileage) and more government incentives.

These assumptions directly determine the average lifetime ownership cost of the vehicle. The dynamics of the cost, across scenarios and world's main markets is presented in the figure below (Fig. 5).

Naturally, as a part of the larger framework of the global energy system, Electric Vehicles fleet is influenced and, in turn, influences a huge number of macroparameters, which are handled by the SCANER modelling complex. However, as the goal of the study is to determine the competitiveness of electric vehicles (expressed in fleet size) and their impact on power sector, major macroeconomic indicators have been fixed and taken as input data. These macroeconomic indicators for the calculations have been derived from ERI RAS and SKOLKOVO Global and Russian Energy Outlook 2019 (Makarov et al., 2019) Conservative and Energy transition scenarios corresponding to Baseline and Favorable scenarios of this study respectively and are presented in Table 4. The overall values of the global demographic and macroeconomic growth are common for both scenarios to ensure regularity of the calculation, at the same time, the projections of oil and gas prices vary significantly in accordance to changes in the global energy balance.

6. Results and discussion

According to the modelling results, by 2040 the number of electric vehicles will increase by a factor of 60–70, compared to 2016 and reach from 12 to 28% of global fleet, depending on scenario. The key sensitive parameters are the rate of battery cost reduction and amount of government subsidies, which determine ownership costs, as has been noted in the previous section. At the same time, by 2040, under the assumptions of the Favorable scenario, by 2040 EVs become competitive even in the low oil price environment and contribute a great deal to the maintenance of these prices. These figures correspond to the forecasts, made by world's leading energy research agencies: IRENA (2019), Bloomberg (2019), OECD/IEA (2018; 2019), OPEC (2018) and BP (2019) (Fig. 6).

Such an increase in electric fleet will significantly alter the energy mix of the transport sector. By 2040 the share of petroleum products will decline from 93% in 2017 to 82% in the Baseline scenario or even 59% in the Favorable scenario. Moreover, Favorable scenario also sees the decrease in net oil products consumption volumes (Fig. 7).

The spread of electric vehicles will lead to an additional increase in global electricity consumption of 7–10% by 2040 (compared to electricity consumption without taking into account electric transport) (Fig. 8).

The growth, however, will be distributed unevenly among the world's countries. Naturally, the greatest increment will come from countries with strong state support for the EVs and localized production: US, China, Japan, EU. In some cases the electricity demand from EVs alone is expected to reach over a third of the country's overall demand (Fig. 9).

At the same time, most of the countries, with the highest expected EV penetration also have ambitious plans for renewable energy development (Fig. 10).

This is significant, because Electric transport is especially prone to amplify the evening and morning peaks of electricity consumption, since the charging is performed mainly either at the workplace at the time of arrival, which coincides with the morning peak, or in the evening after work, right during the evening peak (Fig. 11) and RES are notoriously bad at handling peak loads due to irregular, uncontrollable nature of generation. Thus, there is a looming issue of adaptation to the increase in

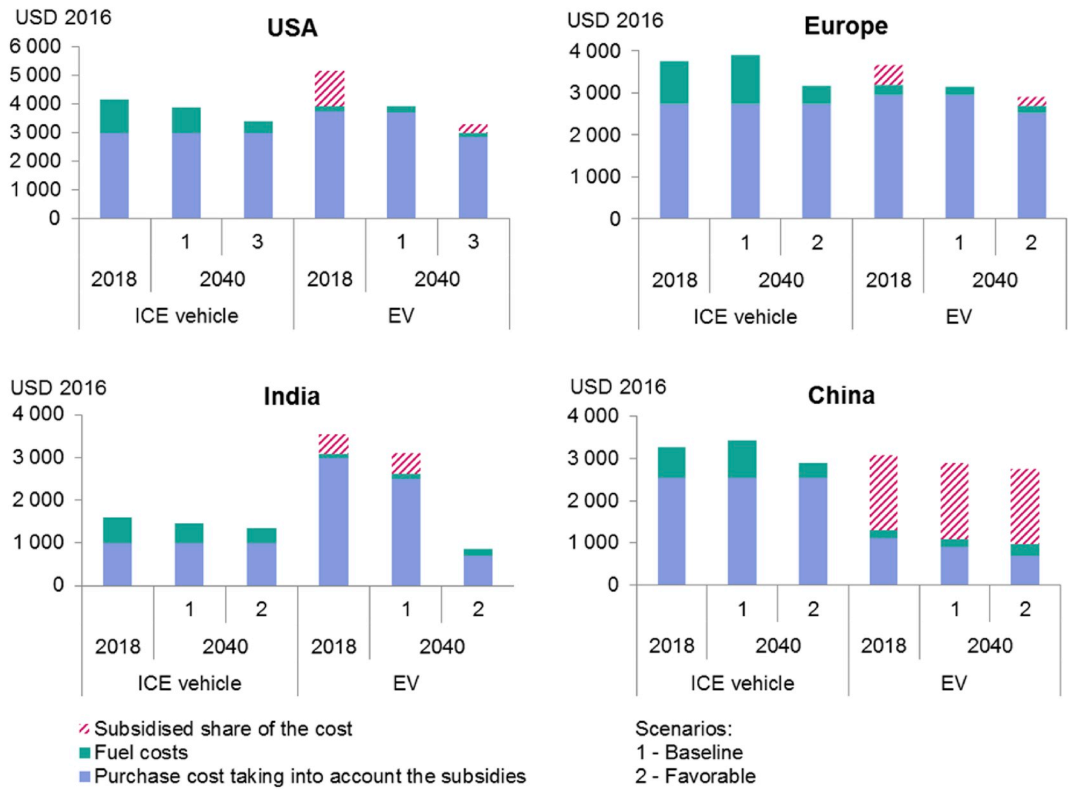

Fig. 5. Scenario assumptions for the average net ownership costs per year of ownership of ICE and electric vehicles in the world's largest markets.
Source: Authors' research

Table 4
Macroeconomic scenario assumptions.

Scenario assumptions	Baseline	Favorable
Average annual GDP growth over the forecast period, %	2.8	
Global population in 2040, bln	9.2	
Oil prices in 2040, USD 2017/barrel	109	60
Gas prices in Europe in 2040, USD 2017/thousand m^3	318	289
Gas prices in Asia (China) in 2040, USD 2017/thousand m^3	409	386

Source: Authors' research, Makarov et al. (2019).

the amplitude of the day and evening peak.

The most obvious way is the expansion of conventional fossil fuel generation capacities to handle the unevenness.

Yet, besides contradicting the countries' drive towards sustainable "green" energy (which the electrification of road transport is a part of), this route will require significant investments in the reconstruction of power transmission lines and distribution networks and may come as a costlier option for energy importers, especially given the carbon taxes, adopted by some countries.

The second alternative comes to the fore – a combination of renewable energy generation and energy storage devices that to accumulate energy from the network during the base load and return it to the network during peak load. This option will allow increasing the share of renewable energy sources in the electric pool, despite the growing fleet of electric vehicles, compensating for the peaks issue. Yet, the organization of power systems on renewable energy with storage devices requires significant changes in the price of peak and base load for the payback of the storage equipment.

7. Conclusions & policy implications

The boom of EVs over the last decade is really a success story of the well-crafted extensive incentive policies adopted by the governments of the world's leading economies. Yet as of 2018, the electric vehicles still cannot be considered fully competitive with the conventional, losing out on a number of characteristics, not only cost-based, but also utilitarian, such as mileage and refueling (charging) time. Only as technological

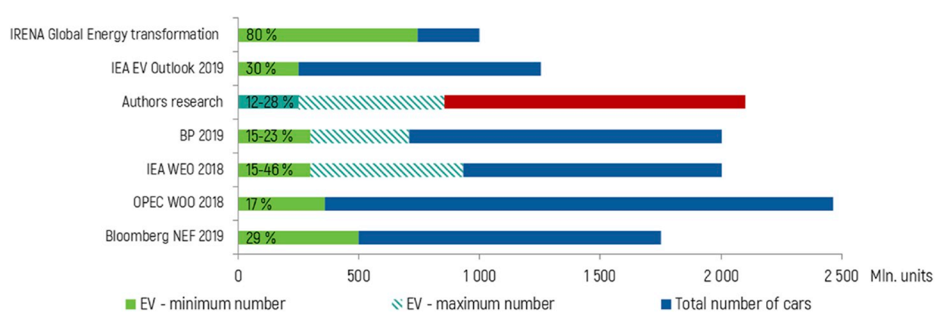

Fig. 6. The number of EVs and their share in the global fleet in 2040 according to Authors' calculations (red column) and various forecast.
Source: Authors' research, IRENA (2019), Bloomberg (2019), OECD/IEA (2018; 2019), OPEC (2018) and BP (2019)

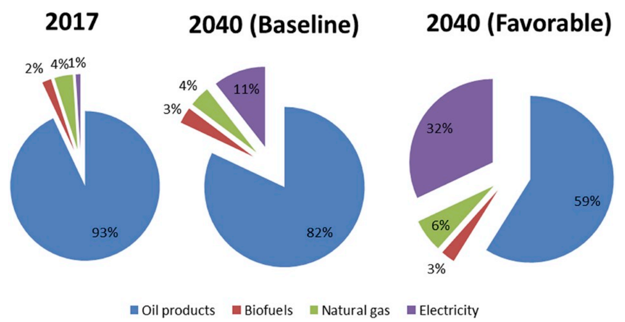

Fig. 7. Transport sector energy demand structure.
Source: Authors' research

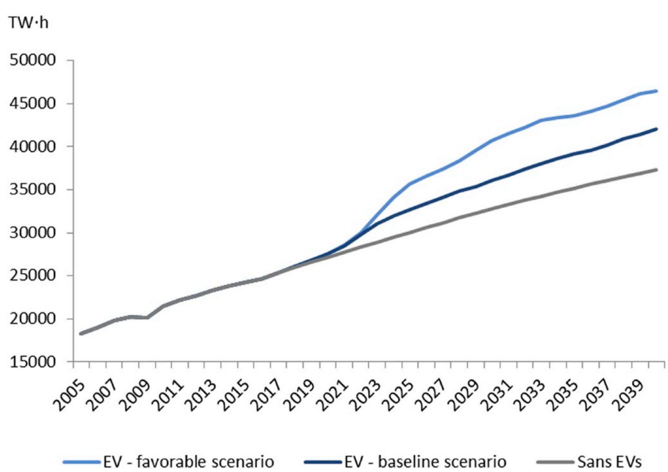

Fig. 8. Scenario forecast of global electricity demand.
Source: IEA (2017b); Author's research

progress runs its course, full competitiveness can be achieved, which we predict around 2035. With the continuation of widespread state support, electric vehicles have a good shot at claiming a considerable share of global fleet over the forecast period. However, as our calculations indicate, even under the best case scenario, by 2040 this share will amount to a quarter maximum. Thus many of the loftier goals and projections of governments and auto-manufacturers appear overly optimistic, the "all-electric future" lies way beyond 2040, if possible at all.

The expansion of electric fleet will entail a fairly significant growth of electricity demand over the forecast period. The main issue, however, is not the net increase in demand for electricity per se, but rather meeting this demand on a day-to-day basis. The increased peak loads, produced by EV charging are a challenge for grid stability in of itself. Even more so when coupled with irregular generation of renewable energy that is expected to grow significantly in the forecast period. Irregularity on top of instability is a recipe for disruptions. While this issue does not seem apparent or pressing now, it is only due the current modest size of electric fleet and RES generation, the governments, pushing for their expansion should already formulate adaptation strategies, to prevent serious consequences in the future.

The business-as-usual solution is to maintain excessive conventional fossil fuel power plants to handle disparities between production and consumption. This is what energy systems will most probably gravitate towards. This route, however, has some major drawbacks. Most obviously, it is not a way of decreasing fossil fuel consumption and anthropogenic emissions, just a switch from petroleum to somewhat cleaner natural gas and, in the worst scenario, cheaper, but severely more carbon-intensive coal. Consequently, energy importers may find themselves even more dependent on a lesser number of suppliers. And last, but not least, it may actually turn out costlier. As projections indicate, by 2040 some of the RES may become an overall cheaper option for major energy importer, especially taking into account the carbon taxes, adopted by these countries (Fig. 12).

Yet to fully utilize RES potential and ensure grid stability, a deep modernization of electric power system is required, with the focus on integration of energy storage technologies. While still being mostly in-development (WEC, 2016), these technologies are capable of evening out inevitable irregularities and radically improve power grid operations, which is vital for renewable energy, but also more than useful in conventional generation. The success of electric vehicles, wind and solar energy indicates, that under thought-out and comprehensive government policies, even the most inertial and complex systems are capable of development and many countries are capable of formulating and

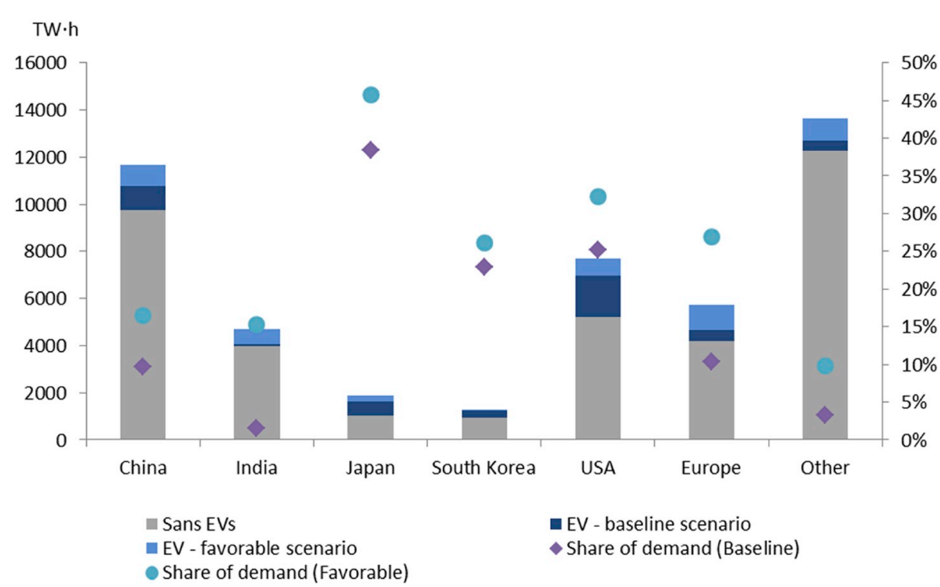

Fig. 9. Increment electricity demand from EV fleet across some of the major world countries in 2040 (left axis) and the share of demand, generated by EVs (right axis).
Source: Author's research

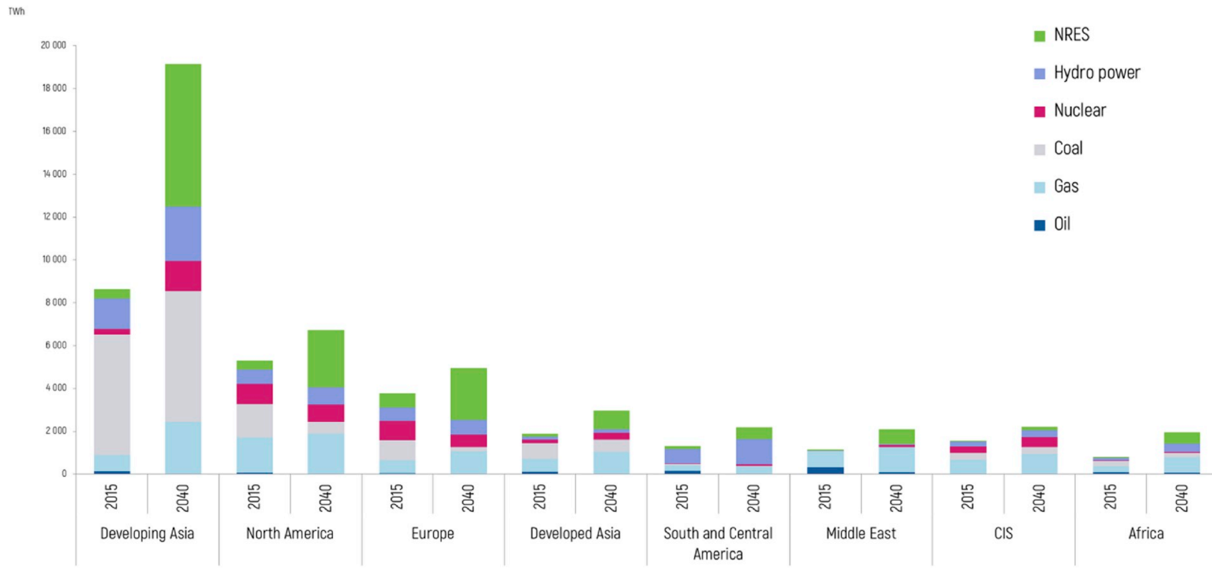

Fig. 10. Electricity production structure of the major world regions.
Source: Makarov et al., (2019) (Energy Transition scenario)

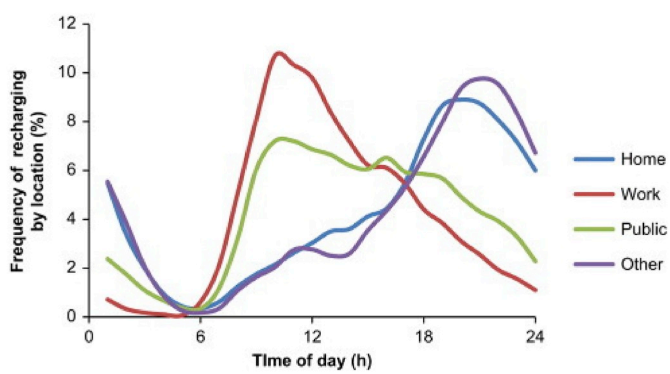

Fig. 11. Distribution of EV owners' preferences for place and time of charging in the north-eastern Britain.
Source: Robinson et al. (2013).

upholding these policies. Expansion of electric transport is certainly a step for humanity's sustainable development. However, to truly make an impact it must be a part of a harmonized system, otherwise it may turn out a step nowhere.

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Declaration of competing interest

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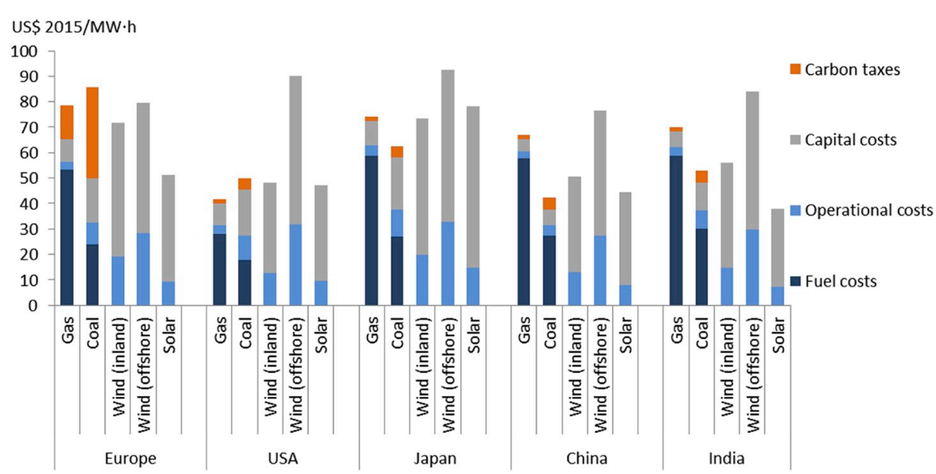

Fig. 12. Specific discounted costs of electricity generation by type of energy source for major energy importers in 2040.
Source: Power Generation Assumptions OECD/IEA (2016), Authors' research

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