Journal of Energy

VOLUME 71 Number 3 | 2022

journal homepage: http://journalofenergy.com/

Electric Vehicle Charging Infrastructure in Croatia – First-Hand Experiences and Recommendations for Future Development

Hrvoje Pandžić, Bojan Franc, Stjepan Stipetić, Franko Pandžić, Matko Mesar, Marija Miletić, Sara Jovanović

***Summary* — One of the most serious obstacles to massive deployment of electric vehicles is insufficient and cumbersome charging infrastructure. Both the number of charging points and their power capacity are often insufficient. On top of that, this new technology often suffers from many issues related to insufficient testing, immaturity and irregular handling. This paper summarizes the issues with the electric vehicle charging infrastructure and describes first-hand experiences with long-range electric vehicle trips originating from Zagreb, Croatia, during 2022. Issues with the charging points locations, power and availability are assessed. Based on these experiences, the paper provides some thoughts on the possible directions of the further development of the electric vehicle charging infrastructure in Croatia.**

***Keywords* — electric vehicles, charging infrastructure, range anxiety**

1. Introduction And Literature Review

Even though the very first electric vehicles appeared already in the nineteenth century, poor battery performance, large weight and short range made them inferior to the internal-combustion-powered vehicles throughout the twentieth century. However, the development of high-capacity and highly efficient lithium-ion battery cells (see [1]), increased concern for the environment and introduction of renewable energy sources (see [2]), and global digitalization of personal transportation systems set battery-powered electric vehicles as the main pillar of the future personal vehicle transport. A survey among early adopters of electric vehicles found that the two main reasons for purchasing an electric vehicle are care for the environment and vehicle design [3]. While studies such as [4] showed that investments in electric vehicles in Croatia are profitable, electric vehicle (EV) adoption is minimal. The shares of EVs are going to rise, fueled by the abovementioned reasons, but also by European legislation promoting cleaner transportation sector. For example, the European Parliament has in early 2023 approved the law banning new sales of diesel vehicles from 2035 [5].

(Corresponding author: Hrvoje Pandžić)

Hrvoje Pandžić, Bojan Franc, Stjepan Stipetić, Franko Pandžić, Matko Mesar, Marija Miletić and Sara Jovanović are with the University of Zagreb Faculty of Electrical Engineering and Computing (FER)

Zagreb, Croatia (e-mails: hrvoje.pandzic@fer.hr, bojan.franc@fer.hr, stjepan.stipetic@fer.hr, franko.pandzic@fer.hr, matko.mesar@fer.hr, marija.miletic@fer.hr, sara.jovanovic@fer.hr)

This work was supported by the Croatian Science Foundation and the European Union through the European Social ´Fund under project Flexibility of Converter-based Microgrids – FLEXIBASE (PZS-2019-02-7747).

The charging infrastructure, which imposes a massive impact on the electric grid, does not develop as rapidly and coherently as the electric vehicle owners would prefer. Although only around 5% of all charging occasions took place at public charging stations [6], long trips require charging points at relevant locations and are important to the users even if such trips occur only a few times per year. The charging infrastructure was promoted through several legal documents from the Clean Energy Package, such as the Energy performance in buildings directive [7] and Renewable energy directive [8]. The reasons for insufficient public charging infrastructure are both the high investment cost and the high operating costs, especially for high-power charging stations. In most countries, industrial loads, besides the consumed energy and network fees, need to pay for peak load on either monthly or annual basis (see [9] for details). Thus, underutilized charging points are not profitable, and there is still an insufficient number of EV owners to justify such investment. However, Croatia is a tourist country and an increasing number of visitors own an EV. For this reason, development of the EV charging infrastructure supersedes the national transportation needs.

The authors in [10] performed a survey during 2018 on the charging infrastructure in the city of Stockholm. The survey aimed at providing responses on who, how and where uses this infrastructure and at collecting user experiences. The authors listed five main challenges identified from the survey:

1. Better control system for parked cars;
2. Improve information (charger types, signs, payment);
3. Increase number of public charging stations;
4. Integrate payment systems;
5. Charger maintenance and monitoring.

The first challenge mainly refers to the fact that a vehicle can be parked at a charging station without charging. This usually happens after the charging session has finished, but the owner did not move their vehicle. Today this issue is resolved in at least two ways. The first one is charging the customers per minute spent at the charger, instead of the charged energy. The second one is charging per minute after the charging session had finished. In this case the customers are still charged per kWh, which is followed by per-minute cost upon the vehicle getting fully charged.

Regarding the second challenge, necessity for better information sharing and education was recognized by authors in [11] who analyzed the challenges for adopting EVs in Croatia. However, a big part of the issue has already been solved. Primarily, the charger types are standardized. Electric vehicles in Europe predominantly

Hrvoje Pandžić, Bojan Franc, Stjepan Stipetić, Franko Pandžić, Matko Mesar, Marija Miletić, Sara Jovanović, Electric Vehicle Charging Infrastructure in Croatia – First-Hand Experiences and Recommendations for Future Development, Journal of Energy, vol. 71 Number 3 (2022), 16–23
https://doi.org/10.37798/2022713414

use Type 2 for AC charging and CCS 2 for DC charging, although there are some vehicles still using CHAdeMO, e.g. Nissan Leaf. On the other hand, the charging stations are highly standardized. The most common 50 kW charging stations in Europe include all three chargers, i.e. Type 2, CCS2 and CHAdeMO. The road signs for charging stations have been standardized as well and there is no problem with recognizing them. However, the gas stations, at least the ones in Croatia, still do not offer a specialized sign for EV charging stations being available at their premises. This makes EV charging less exposed than gasoline, diesel and liquefied petroleum gas (LPG), all of which have a designated sign at the gas stations. Furthermore, the information available online are insufficient and unreliable.

The third issue will remain problematic for the foreseeable future as the number of chargers and their charging speed highly depend on the number of users and their willingness to pay extra for high-speed charging. The authors in [12] assessed the attitudes toward electromobility in Croatia. They found that neither policies aimed at encouraging electromobility, nor the deployed infrastructure have had positive impact on the attitudes toward electric vehicles. A study on a road and a power system segment in Croatia presented in [13] showed that coordination between the transport system planners and power system planners is central to high adoption of electromobility. The authors in [11] emphasize the problem of uneven distribution of charging stations for both domestic adoption of EVs and the highway congestion management during the tourist season.

Payment systems indeed present deep waters for end users. There are numerous applications, usually focused on one country or region in Europe at best. When customer faces a new charging provider, usually it is required to scan a 2D bar code and input credit card data to start charging. This is inconvenient and has other disadvantages, e.g. trying to obtain a company receipt.

Regarding the final issues related to charging maintenance and monitoring, users report often issues with starting the charging process. In this case, calling a telephone number listed at the charging point can solve the issue. However, the unreliable maintenance schedules are still a problem, as are the unavailable call services.

According to [14], range anxiety risk is identified as the second most critical risk for an uptake of electric vehicles with high probability and high impact. Furthermore, the author of [15] states that the public EV charging infrastructure has both the functional and the psychological purpose. Density and reliability of public charging infrastructure increases consumer confidence and reduces range anxiety. The author of [15] also emphasizes that the underutilization of public charging infrastructure should not be considered an "adoption failure". Until novel schemes such as charge sharing presented in [16] take hold, charging infrastructure is the main bottleneck for long-distance EV travel. Lack of such infrastructure can be attributed to very high investment and operational costs. On top of the physical investment at the premises, the installation of EV charging infrastructure also contains connection costs, which are not negligible in most countries. During operation, the EV charging infrastructure operator is not subject only to the energy costs toward its supplier but also to the peak power costs toward the system operators. When having only a small amount of energy supplied to the EVs, these high peak power costs have a strong impact on the per-kWh energy cost.

The main goal of this study is to present specific experiences in taking long EV trips originating from Zagreb, Croatia. By summing the number of leading EV charging providers, Croatia in 2022 offers over 600 public charging locations with over 1.000 charging points. We decided to test some of them and describe our experiences in using the available public charging infrastructure. As all of us are users of conventional vehicles, i.e. petrol- and diesel-powered, this study provides indicators on the chance of adopting new driving and charging patterns and expectations.

II. Trip Experiences

A. Description

We conducted four different trips throughout the year 2022 (see Table I). A map of the trips can be found at [17]. All the trips were taken using Hyundai Ioniq 5 rear-wheel drive, with a 72,6 kWh battery, 160 kW and ULTRA, i.e. the most advanced, equipment package. The producer claimed autonomous range of 481 km, which is not attainable when driving at high speed on highways.

Table I

The Trips Taken in Hyundai Ioniq 5

Trip	Date	One-way distance
Zagreb – Vienna	Tuesday, June 21 2022	360 km
Zagreb – Šibenik	Tuesday, June 28 2022	340 km
Zagreb – Voštane	Tuesday, July 5 2022	430 km
Zagreb – Dubrovnik	Sunday, November 6 2022	650 km

The goal was to test various aspects of e-mobility in Croatia, such as: number of charging stations in rural area, availability, installed power capacity, charging speeds, wait times, travel comfort, travel speed and EV vs fuel car travel times.

III. Trips

A. Zagreb – Vienna

The trip started on Tuesday, June 21, 2022 at 11 am with a fully charged vehicle. Since the distance to Vienna is just under 400 km, the plan was to charge the vehicle before arriving to Vienna. The location for charging was the shopping mall City West in Graz. The vehicle was charged on a 50 kW CCS2 charger operated by Smartics (the reserved amount of money on the credit card was one hundred euros, which was consolidated few days later). The session lasted for an hour and six minutes, which resulted in charging of 35 kWh for 30 Eur. The trip to Vienna was smooth and the final state of charge was 42%. Since this is lower than half of the battery capacity, it was assumed that two charging sessions will be needed on the way back and that the battery will not last to Graz to use the same charger.

The trip back to Zagreb started on Thursday, June 23, around 17 h. After a cumbersome search, an ultra-high-speed 320 kW charging station was identified at Porsche Zentrum Wien-Liesing (address Ketzergasse 120, Vienna), which was not on the way and caused us a detour. To find this charging station we used the Monta app. First try of the charger activation did not work as an error was reported just prior to charging. The vehicle was moved to the other charger, which worked well. We charged 38 kWh for 15.81 Eur. The session lasted 17:25 min. Maximum charging power was 220 kW, but most of the session the power was in between 120 and 148 kW. The table below indicates the reduction in state of charge after charging above 80%. The charging process was cancelled at 89% state of charge, where the charging station reported that additional 14 minutes were expected to reach the 100% state of charge. This ultra-high-speed charging station is located at a secluded location and there was literally nothing to do during the charging process besides admiring the design and the speed of charging.

Hrvoje Pandžić, Bojan Franc, Stjepan Stipetić, Franko Pandžić, Matko Mesar, Marija Miletić, Sara Jovanović, Electric Vehicle Charging Infrastructure in Croatia – First-Hand Experiences and Recommendations for Future Development, Journal of Energy, vol. 71 Number 3 (2022), 16–23
https://doi.org/10.37798/2022713414

TABLE II

REDUCTION OF THE CHARGING POWER AT THE PORSCHE ZENTRUM WIEN-LIESING CHARGING STATION

State of charge	Charging power
82%	101 kW
83%	87 kW
84%	83 kW
85%	74 kW
86%	72 kW
87%	67 kW
89%	55 kW

Fig. 1 Porsche Zentrum Wien-Liesing charging station

After charging to 89%, we went to the shopping mall Westfield Shopping City Sud, only few km away from the Porsche Zentrum Wien-Liesing. The idea was to take advantage of this and slow-charge the vehicle to 100%. Even though Westfield Shopping City Sud is a huge shopping mall, we were only able to find Type 2 charging point with an additional regular shuko plug. Since we did not have a charging cable, we used shuko plug at 3.3 kW. The reserved amount was 20 Eur, however, no cost was claimed in the end. The charging experience at the Westfield Shopping City Sud was by far the worst throughout the trip.

Since we did not have sufficient charge to reach Zagreb, we performed one last charging session at Ionity station at Pesnica pri Mariboru in Slovenia. We used Monta to perform charging at maximum power 220 kW. At 59% state of charge, the charging power was 143 kW, while at 64% state of charge the power was 169 kW. This made us believe that the charging point altered the charging power itself. 39 kWh were charged within 12 minutes. The experience was very nice, which is further spurred by an unprocessed payment, second and final one on the trip.

Overall, the trip was pleasant. Although it took a bit of planning, we did not make many detours and most of the time felt confident about the vehicle's range. The largest disappointment was very basic charging infrastructure at the Westfield Shopping City Sud, while the most convenient charging session was the one in Slovenia.

B. Zagreb – Šibenik

The trip to Šibenik began at about 6 a.m. on Tuesday, June 28th, 2022. The vehicle had been fully charged the night before at the charging station of FER. The stated range of the vehicle was 330 km when switched on, and the distance between FER and the site in Šibenik is 340 km. Therefore, we decided to charge the vehicle at the fast-charging station at INA station - Zir zapad - Mogorić 250. We arrived at the Zir station with about 20% SoC, connected the fast charger and started charging through the ELEN application. The charging process started with a power of 161 kW, continued with a power of 150 kW up to 80 % charge, and ended with a gradually decreasing power up to 95% battery charge. There was an issue with interrupting the charge as I received a mobile phone call during the charge: the ELEN app froze and indicated that the charge was complete, which was not true as it was continuing. Of course, the charging should not be interrupted by disconnecting the charging cable, and we did not want to activate the "safety mushroom", so we called the help-desk telephone number indicated on the charger, explained the situation, and they finished the charging remotely. Soon we received a receipt in the application. A total of 57.96 kWh was consumed at a cost of HRK 4.38/kWh + VAT 13%. The final cost was 286.85 HRK. Recharging took 28:18 minutes, which was not a significant amount of time, nor did it affect the comfort of the trip, as it is a normal break taken during trips in a conventional car to refuel or for the driver to rest. The feeling was compounded by the fact that we were the first in line to recharge, even though there is only one fast charger. We reached Šibenik with a remaining charge of 55%.

The return trip started at 15:30 from Šibenik and we arrived at the INA gas station - ZIR istok - Mogorić 251 with 13% charge. On this side of the highway there are only slow chargers, and the charging was performed with a power of 48.5 kW. Although we were the first in line and there were other non-occupied chargers, charging with a slow charger on the highway is a bad and slow experience. Charging took 1 hour and 9 minutes, and we intentionally exceeded the charging time of 60 minutes to still have enough power for the trip to Zagreb. We charged 53.31 kWh for 69 minutes at a cost of HRK 3.10 + VAT 13%. The final electricity cost was 186.73 HRK, with an additional penalty for overcharging for 9.8

stavka	količina	cijena kn	popust kn	stopa PDV	iznos kn
isporučena električna energija punionica 50 kW dan	53,3060 kWh	3,10		13,00 %	186,73
prekoračenje dozvoljenog trajanja punjenja	9,8333 min	0,80		25,00 %	9,84
			UKUPAN IZNOS RAČUNA		196,57

Fig. 2 Excerpt from the invoice for charging at ZIR istok charging station

minutes of 9.84 HRK (as shown in Figure 2). We drove to Zagreb at lower speed, less acceleration, and we finally reached our destination with a state of charge of 25%.

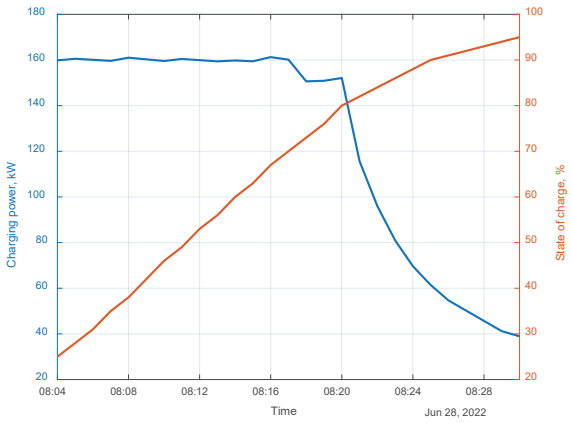
Statistics for both trips are shown in the Table IV, generously shared by ELEN administrators. Interesting detail is that in the 2nd session, the charging duration was 65 minutes and 55 seconds (which would mean 5 minutes and 55 seconds or 5.92 min for penalty interval), but the application charged 69 minutes and 50 seconds (9.83 min for penalty interval).

TABLE III

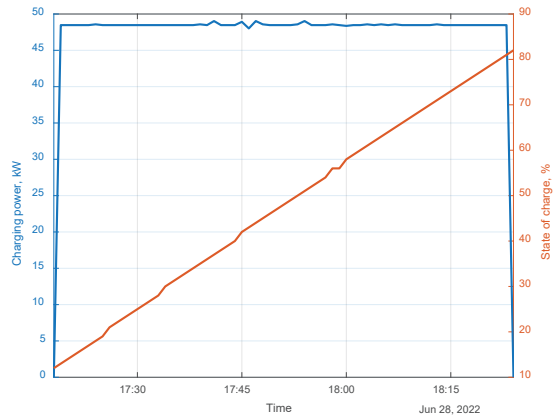
CHARGING SESSIONS AT ZIR ZAPAD AND ZIR ISTOK

Trip Zagreb – Šibenik	Trip Šibenik - Zagreb
S-2022/60550	S-2022/60709
Zir Zapad ultra DC	Zir Istok rapidna AC/DC
28.6.2022.	28.6.2022.
From 28.06.2022. 08:03:08	From 28.06.2022. 17:18:06
To 28.06.2022. 08:31:26	To 28.06.2022. 18:24:02
Vehicle 80% full at 28.06.2022. 08:21:28	Vehicle 80% full at 28.06.2022. 18:23:06
	Vehicle full at 28.06.2022. 18:24:02
Connected from 28.06.2022. 08:02:40	Connected from 28.06.2022. 17:14:19
Connected to 28.06.2022. 08:31:53	Connected to 28.06.2022. 18:24:09
Charging with load to 28.06.2022. 08:30:38	Charging with load to 28.06.2022. 18:24:02
Charging with load duration 00:27:30	Charging with load duration 01:05:55
Time spent 00:28:18	Time spent 01:05:55
Energy consumption 57.96 kWh	Energy consumption 53.31 kWh
Max active power 161.26 kW	Max active power 49.03 kW

Along with the table data for the two sessions, we also received a .csv data log of charging power and SoC, which is shown in the figure below for both sessions.



a) ZIR zapad ultra-fast DC charger



b) ZIR istok rapid AC/DC charger

Fig. 3. Charging profile obtained from data log

C. ZAGREB – VOŠTANE

The primary goal of this trip was to reach the destination – a wind power plant (WPP) named VE Voštane in the south of Croatia, located 430 km from Zagreb, mostly on highway. The V2Load function of the vehicle was used to run the electrical equipment and a laptop while conducting field work in the wind power plant (Fig. 2).

Fig. 4. EV at the wind power plant site

Before starting the trip, a survey was conducted to find suitable charging stations at the destination location. There were no charging stations available on the WPP site, in the vicinity of the WPP, at the hotel we stayed overnight, and most disappointingly nor in the whole town of Sinj. The closest charging station was near the highway in Dugopolje. This was considered while planning the trip. The trip was started on Tuesday, 5 July 2022, with a fully charged EV.

The one-way distance via highway was 430 km, while the total trip length was 849 km, of which 75% was driven on highways. We charged the vehicle four times, for total of 1 h 44 min which resulted in 129.915 kWh of energy. The total price we paid was HRK 571.46 without tax. The overview of the trip is shown in Table IV.

TABLE IV

VOŠTANE TRIP OVERVIEW

Feature	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip total
Mileage	213 km highway	227 km regional road	108 km highway	216 km highway	81 km highway	849 km
Cruise speed	125 km/h	80 km/h	125 km/h	125 km/h	125 km/h	
Battery usage	98% -> 29%	99% -> 52%	93% -> 61%	75% -> 14%	49% -> 22%	

The first charging point we used was 213 km from Zagreb at the Mogorić station. At 125 km/h cruising speed, we arrived with 29% battery charge. At the charging station ELEN DC / 178 kW charger was immediately available and it took 35 minutes for the battery to gain 57.48 kWh. We left the station at 99% state of charge. Figure 5 shows the charging costs, 4.95 HRK/kWh with VAT.

We charged the vehicle the second time at the beginning of our return trip in Dugopolje. The vehicle state of charge was 52% after driving for 227 km on regional roads at 80 km/h and using the V2Load functionality. The Petrol DC / 160 kW charging station was available immediately and in 23 minutes we charged 33.05 kWh into the battery. This resulted in 93% state of charge and cost around 5 HRK/kWh (see Figure 6).

Hrvoje Pandžić, Bojan Franc, Stjepan Stipetić, Franko Pandžić, Matko Mesar, Marija Miletić, Sara Jovanović, Electric Vehicle Charging Infrastructure in Croatia – First-Hand Experiences and Recommendations for Future Development, Journal of Energy, vol. 71 Number 3 (2022), 16–23
https://doi.org/10.37798/2022713414

stavka	količina	cijena kn	popust kn	stopa PDV	iznos kn
isporučena električna energija punionica 178,13 kW dan	57,4840 kWh	4,38		13,00 %	284,51
			UKUPAN IZNOS RAČUNA		284,51

Fig. 5. Excerpt from the invoice for the 1st charging station (ELEN, Croatia)

Tarifa	Stavka	Cijena	Količina	Stopa PDV	Iznos
Ultra brzo punjenje - trajna registracija	Naknada za potrošenu energiju	4.4159 HRK/kWh	33.0500	13.0%	164.92
ZA PLATITI HRK					164.92

Fig. 6. Excerpt from the invoice for the 2nd charging station (Petrol, Croatia)

After 108 km of highway at 125 km/h we charged the vehicle for the third time at Nadin North station operated by ELEN. The DC charger rated at 50 kW was immediately available and we charged for 14 minutes from 61% to 75%. The energy charged was 12.78 kWh and it cost around 3.5 HRK/kWh (see Figure 7).

stavka	količina	cijena kn	popust kn	stopa PDV	iznos kn
isporučena električna energija punionica 50 kW dan	12,7830 kWh	3,10		13,00 %	44,78
			UKUPAN IZNOS RAČUNA		44,78

Fig. 7. Excerpt from the invoice for the 3rd charging station (ELEN, Croatia)

We charged the vehicle for the fourth time at Vukova Gorica station, after driving on highway for 216 km at 125 km/h. The ELEN DC / 50 kW charger was immediately available and in 32 minutes we charged 26.6 kWh into the battery. This took us from 14% to 49% state of charge and at night tariff cost around 2.9 HRK/kWh (see Figure 8).

stavka	količina	cijena kn	popust kn	stopa PDV	iznos kn
isporučena električna energija punionica 50 kW noć	26,5980 kWh	2,57		13,00 %	77,25
			UKUPAN IZNOS RAČUNA		77,25

Fig. 8. Excerpt from the invoice for the 4th charging station (ELEN, Croatia)

We charged the vehicle for the fifth and final time in Zagreb, at FER. The charging station was occupied for 3.5 hours and our vehicle was third in line. Charging lasted over 1.5 hours at 50kW rated charger. The vehicle was charged from 22% to 100%, taking in 60.06 kWh. As the charging station is operated by FER, the charging was done at no cost.

Generally, all the visited charging stations were operational, providing charge speeds as specified. DC chargers of speeds 50 kW (Fig. 14) and more were available at each charging points as specified. There were no waiting queues, no technical, software, nor any payment issues. Table V gives an overview of the charging data for this trip.

Fig. 9. Hyundai IONIQ 5 charging at Janjče ELEN charging station

Hrvoje Pandžić, Bojan Franc, Stjepan Stipetić, Franko Pandžić, Matko Mesar, Marija Miletić, Sara Jovanović, Electric Vehicle Charging Infrastructure in Croatia – First-Hand Experiences and Recommendations for Future Development, Journal of Energy, vol. 71 Number 3 (2022), 16–23
https://doi.org/10.37798/2022713414

TABLE V

VOŠTANE TRIP CHARGING DATA OVERVIEW

Feature	Charge 1	Charge 2	Charge 3	Charge 4	Trip total
Charging station type	ELEN DC / 178 kW	Petrol DC / 160 kW	ELEN DC / 50 kW	ELEN DC / 50 kW	FER AC/DC 98 kW
Max power rated	178 kW	160 kW	50 kW	50 kW	50 kW
Max power measured	158 kW	163 kW	49 kW	49 kW	not observed
Energy transferred	57.48 kWh	33.05 kWh	12.78 kWh	26.60 kWh	not observed
Charge time	35 min	23 min	14 min	32 min	not observed
Battery after charge	99%	93%	75%	49%	100%
Price (without 13% tax)	4.38 HRK / kWh	4.42 HRK / kWh	3.10 HRK / kWh	2.57 HRK / kWh (night)	571.46 HRK (w/o FER)

On the way to the WPP Voštane, the first half of the trip was driven using the highway and at highway speed limits. Upon exiting the highway, the trip was continued with a fully charged EV. The second part of the trip was driven using regional roads at lower speeds. This change in driving speeds resulted in a dramatical increase of the EV's range, enabling us to reach the desired location with a higher-than-expected battery charge state. Although we started the trip with some range anxiety, due to knowing there are no charging points at our destination, after driving the regional roads and arriving at the target location with a more than 50% battery charge state, the range anxiety was completely gone.

On the way back, we charged the EV right away to (almost) full charge. The return trip was driven completely on the highway at speeds a bit under the speed limits (some experience was gathered on the first trip). Unfortunately, on the way back, in the direction from the Adriatic coast to Zagreb, there are no ultra-high-speed charging stations (so the tourists will leave the country after the vacation a bit slower than they arrived). All the charging stations visited were of max 50 kW DC, CCS2 / CHAdeMO. At the end of the trip, although battery charge levels dropped to 14%, there was no range anxiety as there are plenty of charging stations with free slots available. On the other hand, adding one and a half hour to a 5-hour trip took its toll and pushed us a step back to the old-fashioned internal combustion engine car.

D. Zagreb – Dubrovnik

The trip started on Sunday, November 6 2022 around 8:50 in the morning with 94% of battery charge. This was the longest trip we took (around 650 km one-way) which turned out to be the most eventful and challenging as well. We tested the battery capacities on higher speeds in the first part of the trip so the first mandatory stop was Janjče Crodux gas station (Figure 10); 170 km from the starting point. The vehicle was charged using 50 kW CCS2 charger operated by ELEN from 16% to 44% battery capacity in 25 minutes (110 km of range). The whole experience was unpleasant as the designated app through which payment is done froze and crashed multiple times and emergency eject button had to be used to unplug the vehicle. Additional funds were reserved (HRK 400, which were subsequently refunded) for restarting the app and repeating the procedure of charging in an attempt to unplug the vehicle normally.

Fig. 10. Hyundai IONIQ 5 charging at Janjče ELEN charging station

The next stop was only 41 km away (gas station Zir) as the 160 kW ELEN supercharger was available. Everything went smoothly and in 20 minutes the battery was fully charged.

Dugopolje Petrol ABB was the next stop, 180 km away from Zir. The charging station was previously used in the Voštane trip and we expected good performance from it, which proved to be a mistake. Firstly, a new app had to be installed which was essentially the same as every other with a different logo. The charging would fail at the very last step where charger-vehicle communication couldn't be established. Both 50 kW CCS2 chargers behaved the same. For each charging attempt the app would reserve around HRK 450; in total over HRK 2200 for both chargers without actually providing any service. This created an additional problem as the funds were not promptly released. Furthermore, we were unable to resolve the issue through multiple attempts at contacting customer support. The only positive factor of this charging station was its close proximity to a shopping mall.

The next nearest charging station was a Tesla station which turned out to be unusable for other car manufacturers, as this service is not available in Croatia. Next, we tried HT Dugopolje charging station which either doesn't exist or was inaccessible, behind a closed fence. At this point, the battery range had decreased to less than 25 km, so extreme measures were taken to conserve power and avoid being stranded and further delayed with more complications. Another HT charging station in the nearby parking garage seemed to be the solution. Yet another app needed installing with a similar interface but slightly different functionalities. A card deposit of 50, 100, 200 or 500 HRK (only options) needed to be made to process eventual payment. Charging (50 kW CCS2) failed at the charger-vehicle communication again. This time customer support was available. Even though the information available online marked the station as functional, the support was aware of the issue. The customer support directed us to City Center One Split with assurance of a working charging station. Furthermore, the allocated funds through the app (HRK 200) were never refunded.

The City Center One Split charging station wasn't easy to find because of insufficient instructions on the parking lot. It was a 22 kW output but no charging cable was provided. We used our own cable with which we were able to utilize only 11 kW of power. The usage instructions were also confusing as it stated requirement of another app being installed but turned out to be free of charge. The charging time was 1h to gain 11 kWh or 40 km of range (15 to 55 km) just to be able to make it to a higher output charger at the highway.

The next station was a much needed 50 kW ELEN charger in Dračevac, Split, pictured below. A 30 min charging process was enough for additional 167 km of range (19% – 55% of battery charge). The charger was located in the middle of nowhere surrounded by what seemed to be a make-shift waste disposal but was easy to find using online instructions and was functional. As the destination was still 250 km away, another stop was deemed necessary to be certain and avoid any further unpleasantries.

Fig. 11. Hyundai IONIQ 5 charging at Dračevac ELEN charging station

The last stop before the destination was Rašćane Gornje gas station back on the highway where another ELEN 50 kW CCS2 charger was located. The charger was hard to find on the large parking lot at night as it wasn't marked or illuminated in any way. The final charge of the trip took 77 mins in total (26 – 81 % in 53 mins, 81 – 89 % in 9 mins and 89 – 100 % in 15 mins). Upon arriving to the destination in Cavtat, the battery charge was 65 % with an estimated range of 203 km. The time of arrival was around 22:30 h. In other words, a trip of 650 km (with detours and charging) took almost 14 hours to complete. On a scale of 0 to 10, we would rate the experience as 1 just for the sake of making it to the destination.

Valuable insight was gained during this trip:

- Charging stations in Croatia that are located off the highway and outside of peak tourist season are often poorly maintained or not maintained at all and are to be avoided if possible.
- Charging stations along the highway seem to be functional and responsive and are recommended.
- Customer support for some chargers (Petrol) is unavailable either outside tourist season or on weekends.
- Power consumption must be frugal during long trips with electric vehicles, even more than expected.
- ELEN charging stations proved the most trustworthy, but the reason might be their placement on the highway, while the Petrol and HT stations were located next to shopping centers.
- Have trip companions to kill time and have more resources.

IV. Conclusion

This paper provided first-hand long-trip experiences with a Hyundai Ioniq 5 with a large-capacity battery in Croatia during 2022. These trips ranged from 340 km in each direction, i.e. Zagreb-Šibenik, to over 600 km in each direction when traveling from Zagreb to Dubrovnik. The trips predominantly used fast highways. We did not experience issues with the vehicle itself, but we did experience issues with the charging infrastructure. Our observations are as follows:

- Croatian highways are equipped with enough charging stations. However, more than several charging sessions required calling the customers' service to start the charging process. Such user experience is simply not good enough in times when the sales of electric vehicles is about to pick up and become predominant. Moreover, fast charging stations are available only in one direction of the highway which makes the trips from the coast toward Zagreb slower.
- More serious issues are related to poor directions for reaching charging stations located outside the highways (both in Croatia and Austria) and communication errors making the charging impossible. As opposed to gas stations, which pretty much always have enough gas to fuel any vehicle, which are predominantly open non-stop and which have a person operating the station, the fact that there is no live person to help with the EV charging process makes drivers uncomfortable and always in need of plan B.
- Charging an electric vehicle at different locations and countries calls for installation and getting used to multiple apps, which wastes a lot of the drivers' time.
- We did not experience waiting times for a charging station to free up, however, that could be a serious issue during the tourist season.
- Charging times are still long, even with fast charging stations operating at 50 kW, which is the most common type of stations. For a high-capacity battery this still requires over one hour to charge, which is simply a lot, especially as there is not much to do while the vehicle is charging. An idea might be to couple fast charging stations with entertainment centers, e.g. shopping malls, restaurants, children fun centers, etc., to make long waiting times easier to handle.
- Electric vehicle, at least with the current charging infrastructure, calls for different driving style. Namely, if a 50 kW fast charging station is the fastest charging option, the most time-efficient driving speed is just above 100 km/h. Faster driving significantly reduces the range, and since the battery takes a lot of time to charge, the overall traveling time is increased. This is a major difference as compared to the petrol or diesel cars.
- Ultra-high-speed charging stations (180 kW and above) are a great solution for electric vehicle drivers on highway, as the vehicle is charged within 15-20 minutes, which is bearable for most drivers. However, such stations are scarce both in Croatia and Austria. In Croatia, currently there is only a single ultra-high-speed charging station on the highway from Zagreb to the south, and zero in the opposite direction. Similarly, it takes some severe detours in Austria to reach ultra-high-speed charging stations. The situation is somewhat better in Slovenia, which has few ultra-high-speed charging stations at gas pumps located on highways.

To conclude, the charging infrastructure requires better planning and the current experience is still not satisfactory for a regular driver. Focus should be put on high-speed charging stations that would make the charging experience very similar to the one at the gas stations. However, the development of ultra-high-speed charging stations is not economic to the charging point operators as the connection costs and peak (monthly) power cost are too expensive to be paid off through an infrequent use of the charging points.

Hrvoje Pandžić, Bojan Franc, Stjepan Stipetić, Franko Pandžić, Matko Mesar, Marija Miletić, Sara Jovanović, Electric Vehicle Charging Infrastructure in Croatia – First-Hand Experiences and Recommendations for Future Development, Journal of Energy, vol. 71 Number 3 (2022), 16–23
https://doi.org/10.37798/2022713414

References

[1] V. Bobanac, H. Bašić, and H. Pandžić, "Determining Lithium-ion Battery One-way Energy Efficiencies: Influence of C-rate and Coulombic Losses", in *IEEE EUROCON 2021 - 19th International Conference on Smart Technologies*, Jul. 2021, pp. 385–389. doi: 10.1109/EUROCON52738.2021.9535542.

[2] L. Punda, T. Capuder, H. Pandžić, and M. Delimar, "Integration of renewable energy sources in southeast Europe: A review of incentive mechanisms and feasibility of investments", *Renew. Sustain. Energy Rev.*, vol. 71, pp. 77–88, May 2017, doi: 10.1016/j.rser.2017.01.008.

[3] I. Vassileva and J. Campillo, "Adoption barriers for electric vehicles: Experiences from early adopters in Sweden", *Energy*, vol. 120, pp. 632–641, Feb. 2017, doi: 10.1016/j.energy.2016.11.119.

[4] M. Gržanić, A. Hrga, and T. Capuder, "Profitable Investment in PV and BES Integrated with EV Charging Stations in Croatia - Myth or Reality?", in *2022 7th International Conference on Smart and Sustainable Technologies (SpliTech)*, Jul. 2022, pp. 1–6. doi: 10.23919/SpliTech55088.2022.9854341.

[5] "EU ban on sale of new petrol and diesel cars from 2035 explained | News | European Parliament", Nov. 03, 2022. https://www.europarl.europa.eu/news/en/headlines/economy/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained (accessed Apr. 13, 2023).

[6] S. Hardman *et al.*, "A review of consumer preferences of and interactions with electric vehicle charging infrastructure", *Transp. Res. Part Transp. Environ.*, vol. 62, pp. 508–523, Jul. 2018, doi: 10.1016/j.trd.2018.04.002.

[7] *Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (Text with EEA relevance)*, vol. 156. 2018. Accessed: Apr. 13, 2023. [Online]. Available: http://data.europa.eu/eli/dir/2018/844/oj/eng

[8] *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance.)*, vol. 328. 2018. Accessed: Apr. 13, 2023. [Online]. Available: http://data.europa.eu/eli/dir/2018/2001/oj/eng

[9] N. Čović, F. Braeuer, R. McKenna, and H. Pandžić, "Optimal PV and Battery Investment of Market-Participating Industry Facilities", *IEEE Trans. Power Syst.*, vol. 36, no. 4, pp. 3441–3452, Jul. 2021, doi: 10.1109/TPWRS.2020.3047260.

[10] E. Sunnerstedt, M. Xylia, and A. Sjögren, "The City of Stockholm experiences with charging infrastructure for EVs", in *32nd International Electric Vehicle Symposium (EVS32)*, Lyon, Mar. 2019.

[11] M. Emanović, M. Jakara, and D. Barić, "Challenges and Opportunities for Future BEVs Adoption in Croatia", *Sustainability*, vol. 14, no. 13, Art. no. 13, Jan. 2022, doi: 10.3390/su14138080.

[12] M. Mutavdžija, M. Kovačić, and K. Buntak, "Assessment of Selected Factors Influencing the Purchase of Electric Vehicles—A Case Study of the Republic of Croatia", *Energies*, vol. 15, no. 16, Art. no. 16, Jan. 2022, doi: 10.3390/en15165987.

[13] I. Pavić, N. Holjevac, M. Zidar, I. Kuzle, and A. Nešković, "Transportation and power system interdependency for urban fast charging and battery swapping stations in Croatia", in *2017 40th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO)*, May 2017, pp. 1465–1470. doi: 10.23919/MIPRO.2017.7973652.

[14] T. Capuder, D. Miloš Sprčić, D. Zoričić, and H. Pandžić, "Review of challenges and assessment of electric vehicles integration policy goals: Integrated risk analysis approach", *Int. J. Electr. Power Energy Syst.*, vol. 119, p. 105894, Jul. 2020, doi: 10.1016/j.ijepes.2020.105894.

[15] J. J. Bakker, "Contesting range anxiety : the role of electric vehicle charging infrastructure in the transportation transition", Master, Eindhoven University of Technology, Eindhoven, 2011.

[16] P. Chakraborty *et al.*, "Addressing the range anxiety of battery electric vehicles with charging en route", *Sci. Rep.*, vol. 12, no. 1, Art. no. 1, Apr. 2022, doi: 10.1038/s41598-022-08942-2.

[17] H. Pandžić *et al.*, "Ioniq 5 Trips", 2022. https://www.google.com/maps/d/edit?mid=1Kez_o-rZmHD4pY1DqRJqP2bnQ6w9MQo&usp=sharing (accessed Apr. 13, 2022).