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Technical Feasibility Assessment of Electric Vehicles: An Abu Dhabi Example

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***Abstract*—Recently, Electric Vehicles (EVs) have gained much attention as a potential enabling technology to support CO_2 emissions reduction targets. Relative to their internal combustion vehicle counterparts, EVs consume less energy per unit distance, and add the benefit of not emitting any carbon dioxide in operation and instead shift their emissions to the existing local fleet of power generation. However, true success of EVs depends on their successful integration with the supporting infrastructure systems. Building upon the recently published methodology of the same purpose, this paper presents an systems-of-systems example assessing the impacts of EVs on these three systems in the context of Abu Dhabi. For the physical transportation system, a microscopic discrete-time traffic operations simulator is used to predict the kinematic state of the EV fleet over the duration of one day. For the impact on the Intelligent Transportation System (ITS), the integration of EVs into Abu Dhabi is studied using a Multi-Domain Matrix (MDM) of the Abu Dhabi Department of Transports ITS. Finally, for the impact on the electric power system, the EV traffic flow patterns from the CMS are used to calculate the timing and magnitude of charging loads. The paper concludes with the need for an Intelligent Transportation-Energy System (ITES) which would coordinate traffic and energy management functionality.**

I. Introduction

The transportation-energy nexus as brought about by electric vehicles and trains couples the performance of each supporting infrastructure system. In the road transportation system, and much like other vehicles, EVs add to road and parking congestion; but does so in a way that is constrained by the vehicle range and charging patterns. In the electrical energy system, the charging requirement places an energy demand that can be studied in terms of both energy as well as instantaneous power withdrawals. Finally, modern day road transportation systems are being upgraded with supporting information technologies called Intelligent Transportation Systems. Such systems help maintain situational awareness for drivers and traffic control centers alike. If EVs are to be accepted by everyday consumers, they must interface and interact with these three systems.

This paper presents a *full-scale* integrated example assessment of the impacts of EV on these three systems in the context of Abu Dhabi Island. The paper begins in Section II with some background material necessary for the execution of a holistic EV technical feasibility assessment. The paper then proceeds in Section III to discuss how the previously published assessment methodology [1]–[3] was implemented in this specific example. The body of the work focuses on presenting the results of the assessment in Section IV. Finally, Section V discusses the results in the context of the need for “Intelligent Transportation-Energy Systems” that do not just manage traffic but simultaneously manage electrical energy. The paper is brought to a conclusion in Section VI.

II. Background

Prior to executing a holistic EV technical feasibility assessment, it is necessary to highlight the requirements for such an assessment and to recall some of the performance measures that can be applied. Each of these is addressed in turn in the following two subsections.

A. Requirements for Holistic Technical Feasibility Assessment of EVs

As mentioned previously, this holistic technical feasibility assessment considers the interactions that an EV has with three supporting infrastructure systems: the road transportation network, the electrical grid, and the intelligent transportation system. This subsection identifies some of the requirements necessary for the assessment of each infrastructure system in turn.

One of the main distinguishing features of a traffic simulation appropriate for EVs is that it must be distinguish EVs from the rest of the ICV fleet. This implies a number of other functional requirements. A microscopic simulator keeps track of each individual vehicle in the simulation and differentiate between ICV’s and EV’s. This differentiation allows the simulated motion of ICVs and EV to take into account technical differences in vehicle characteristics. A discrete-time simulator is able to simulate the time dependent location and speed of each vehicle. In an EV traffic simulation, it is necessary to analyze the individual location and speed to determine the charging patterns for further analysis of the charging loads. Therefore, a discrete-time simulator is recommended. A deterministic simulator provides predictable results of traffic behavior. In an EV simulation, analyzing the charging loads are determined by the traffic behavior. To study the charging loads, a deterministic simulator will give results that are determined by predictable results based on previously detected parameters of an EV. Finally, an operations-oriented simulator assumes the transportation network is fixed over the simulation duration. For an EV simulation, it is necessary to set have a fixed transportation network to simulate the EV behavior over the simulation time period [2], [3].

A traffic simulation appropriate for EVs must also recognize the electrical aspect of the vehicle in terms of its electrical charging and discharging. In terms of charging, various types of chargers are available and each has a set of parameters. For example, a type II charger can charge at an average rate of 19kW while a type III charger can charge at 50kW [4]. The traffic simulator needs to have the ability to distinguish between charging stations to monitor each charging station load separately. In terms of discharging, the user must be able to input a set of parameters that the simulator will use to calculate a vehicle's state of charge over time. To calculate the discharge rate, the user needs to have the ability to input a number of parameters. For example, the EV discharges its battery at a higher rate at higher temperatures. Additionally, EVs require energy for air-conditioner usage which depends on both the driver's attitude as well as the air temperature [2], [3].

In summary, the functional requirements for a traffic simulator recommended to simulate EV traffic behavior are the following [2], [3]:

1) Microscopic - Ability to differentiate between ICVs and EVs
2) Discrete-time - Ability to simulate the time dependent location and speed of each vehicle
3) Operations-oriented - Assumes the transportation network is fixed over the simulation duration
4) Deterministic - Provides predictable results of the traffic behavior
5) Monitors state of charge

In regards to the intelligent transportation system, the previously published assessment methodology proposed the usage of the Unified Modeling Language (UML) as the defacto tool modeling information systems [1]–[3]. Such an approach, however, assumes that the ITS is at a stage of full implementation rather than in the design stage. Instead, this work utilizes a design structure matrix (DSM) and its generalization the multi-domain matrix (MDM) to present the results in Section IV.

A Design Structure Matrix (DSM) is a network-modeling tool commonly used to represent the elements comprising a system and their interactions [5]. DSM's are essentially N^2 diagrams that are structured in such a way as to facilitate systems-level analysis and process improvement [5]. It is also is suited to applications in the development of complex systems such as the systems modelled in this project.

However, the DSM only concerns itself with the form relationships between components. Instead, the MDM provides an efficient approach to relate form to function to stakeholder needs. As shown in Figure 1, submatrices 1, 2 and 3 show the interfaces within a single domain; be it functional requirements, components, or stakeholders. Furthermore, submatrices 4, 5 and 6 show the relationships between any two of the three domains. Keeping track of these interfaces and relationships can guide later stages of the design of an ITES especially as it begins to integrate EVs. This reverse engineering analysis will help demonstrate how the objects in the ITES interact.

	Functional Requirements	Components	Stakeholders
Functional Requirements	1		
Components	4	2	
Stakeholders	5	6	3

Figure 1: Multi-Domain Matrix (MDM)

B. Performance Measures

When considering a road-transportation energy nexus, it is important to recognize that the fleet of electric vehicles require four functions which need to be coordinated simultaneously: dispatching of routes, management of charging queues, dispatching of charging and potentially vehicle-2-grid stabilization. This subsection proposes performance measures to quantify how well these functions are achieved.

The transportation system performance measurement of the EV integration scenarios focuses on the EV "quality of service" (QoS) so as to directly address many of the availability concerns expressed in EV adoption public attitude surveys [6]. Quantitatively, the EV QoS can be defined as the percentage of time that the EV fleet is in motion T_m divided by the total time required for travel including charging T. Here, the travel time T_i of the i^{th} EV trip is specifically defined as the difference between when the EV is requested for travel service t_{r_i} and the moment of arrival t_{a_i}.

$$QoS = \frac{\text{Time in Motion}}{\text{Total Travel Time}} = \sum_{i}^{trips} \frac{t_{m_i}}{[t_{a_i} - t_{r_i}]} \quad (1)$$

The power system performance measurement of the EV integration scenarios focuses on the grid's safety from a local perspective. In that regard, power line ratings place a physical limit on the amount of transferred active power. Given a set of N_l lines, a given line i may have a line limit P_i^*. Following NERC guidelines on the operation of transmission facilities, a line safety criterion SC can be defined as the average amount of excess active power in all the lines over a simulation period T_s:

$$SC = \frac{1}{N_l T_s} \sum_{i}^{N_l} \left[\frac{1}{P_i^*} \int_0^{T_s} f_i(t) dt \right] \quad (2)$$

where

$$f(i) = \begin{cases} P_i(t) - P_i^* & if P_i > P_i^* \\ 0 & otherwise \end{cases} \quad (3)$$

III. Assessment Methodology

Given the assessment requirements and performance measures of the previous section, the discussion can shift to the discussion of the methodology by which the holistic assessment of electric vehicle technical feasibility integration was carried out. In that regards, the previously published assessment methodology was applied [1]–[3]. This section highlights some of the essential elements of that methodology and describes the unique aspects of the research methodology found within this study.

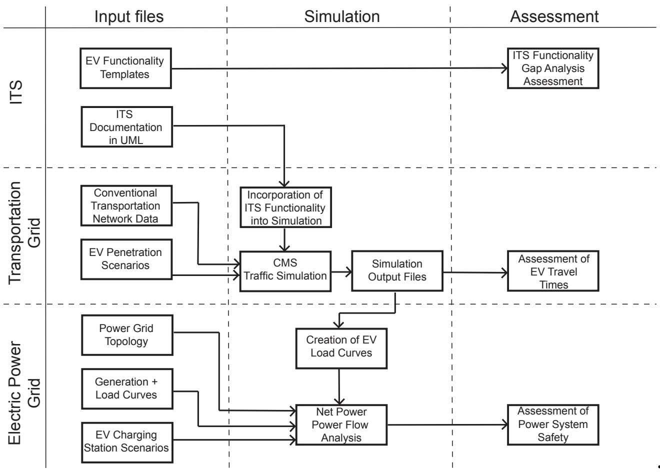

Figure 2: Methodology of Assessment [1]–[3]

Figure 2 provides a schematic of the assessment method as a whole [1]–[3]. The EVs interact with three interconnected 'systems-of-systems': the (physical) transportation system, the electric power grid, and the ITS. For the traffic system, a microscopic discrete-time traffic operations simulator is used to study the kinematic state of the EV fleet at all times. For the electric power system, an analysis of power flows is used to determine the electrical charging loads required by the EV traffic usage patterns. Finally, an ITS functionality gap analysis is completed in relation to an EV functionality template.

A. *Clean Mobility Traffic Simulator*

While in theory any traffic simulator that meets the requirements described in Section II-A, this work applies the "Clean-Mobility Simulator" (CMS) because it embodies all there required functionalities of an EV simulator. As a discrete-time simulator, it gives a record of each EV's kinematic state and state of charge with respect to time. As a result, the CMS is a tool that has potential to help understand whether EVs, with their technical limitations, meet the needs of transportation behavior in Abu Dhabi. The CMS also has the ability to simulate traffic behavior while determining the energy demand and charging curves of EVs. A schematic design of the CMS behavior is shown in Figure 3.

B. *Abu Dhabi Base Simulation Setup*

Once, the CMS was chosen as the traffic behavior simulator a number of steps were taken to develop a detailed and well-calibrated traffic behavior simulation base case of Abu Dhabi Island. Figure 4 demonstrates the process of development. First, Abu Dhabi island was chosen as the geographical scope of the traffic simulation as it is the most densely populated geographical location in Abu Dhabi emirate. Abu Dhabi island, also has the highest likelihood of EV adoption. Thirdly, the

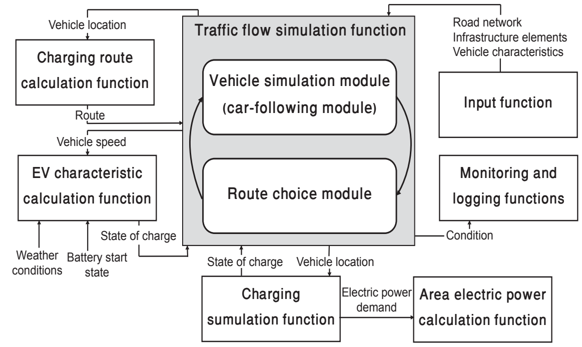

Figure 3: Schematic design of the CMS behavior [7]

data for CMS simulator was gathered from different sources which include: traffic counts provided by the Abu Dhabi Department of Transportation (ADDOT), GPS loggers measured by Mitsubishi Heavy Industries, and STEAM simulator parameters of the 2015 model from DOT. Next, the road transport network was determined and the CMS input file was generated. Finally, to complete the Abu Dhabi base case, the model was validated and calibrated by being compared to the STEAM model results.

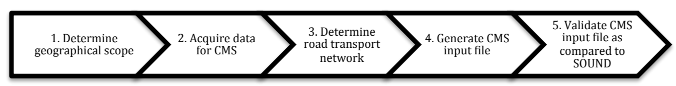

Figure 4: Development Process of Abu Dhabi's Base Traffic Simulation Case

The outcome of this procedure was a detailed and well-calibrated Abu Dhabi Island traffic simulation base case implemented in the CMS for EV penetration study. To that effect, a number of hypothetical cases are added on top of this normal traffic baseline. In this example assessment, six cases are formulate in the simulation experimental design. Three values of EV penetration are assessed: 3%, 5% and 10%. Additionally, two charging system design called "Limited Dense" and "Limited Dense Mixed" are tested. Both of these configurations are meant to emulate a limited roll out EVs on the Abu Dhabi and differ in their usage of Type II and Type III chargers. Figure 5 and 6 show the type and geographic placement of the chargers for each configuration.

Figure 5: Limited Dense Charging Station Design Map

IV. Integrated Assessment Results

Once the assessment methodology has been customized to this Abu Dhabi example, the discussion can proceed to present the results of the integrated assessment. It is important to recognize that this particular example assessment addresses

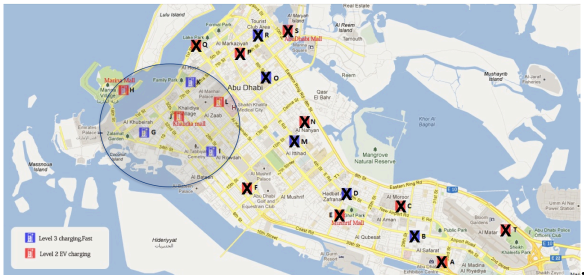

Figure 6: Limited Dense Mixed Charging Station Design Map

EVs "naively-integrated" without sophisticated coordination of vehicle dispatch, charging queues, charging dispatching and vehicle-2-grid stabilization. In such a way, it gives a baseline sense of the potential effects of EV integration without such advanced control functions. The Transportation, power and intelligent transportation systems are taken in turn.

A. Transportation System Assessment

The results of the transportation system assessment are summarized in Figure 7. In general, as the penetration increases, the QoS generally decreases. This degradation effect is likely due to longer charging queues. For example, the lowest QoS is shown in both 10% penetration levels. With a fixed set of charging stations and an increasing number of EVs, the waiting time of each vehicle to charge increases. This demonstrates the importance of the number of charging stations in a high penetration ratio. To maintain a high QoS, it is essential to increase the number of charging stations as the penetration of electric vehicle increases.

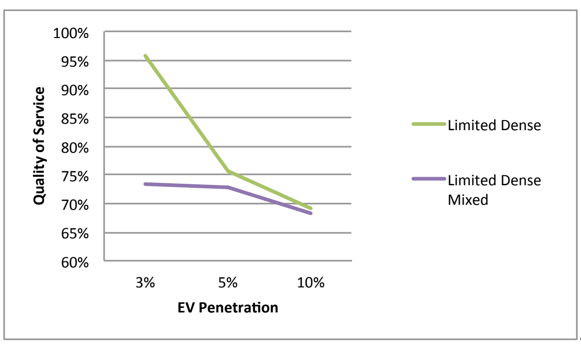

Figure 7: Quality of Service Results

The simulations have demonstrated that the integration of electric vehicles in to the transportation system can have a significant detrimental impact on the quality of service provided by the electric vehicles. The implications of this are profound depending upon the EV use case. Left unmitigated in public sector or commercial applications, such a degradation of quality of service can result in either direct or indirect loss of revenue. For example, EV taxi or EV bus passengers may decide to use other modes of transport as they experience delays in their travel itineraries. Government commercial fleets may find that the use of EV results in an impaired ability to execute their daily tasks. Such impacts can ultimately have negative word-of-mouth knock-on effect in the adoption rate of private users. Therefore, the ultimate viability of electric vehicles depends on technical efforts to mitigate the actual and perceived degradations in quality of service. One can frame the cost of these technical efforts within an ROI decision framework given an understanding between the relationship of quality of service and lost revenue [8].

The technical efforts to mitigate the degradation of quality of service ultimately requires that charging stations are geographically spread out across the city or the area of service. This is equally true for relatively small EV penetration rates. Technically speaking, a large number of charging stations geographically spread throughout the city may lead to acceptable quality of service in such circumstances. However, the aggregate value of charging stations per EV would be relatively high and potentially cost prohibitive on the supply side. EV users, coming from the conventional mentality of ICV transport, probably have a limited willingness to subsidize charging station infrastructure despite potentially demanding QoS requirements. An alternate solution would be target use cases where the EV routes are well known and quantified. In such cases, charging station placement can be concentrated along these routes. Regardless of whether the EV adoption scenario is geographically broad or limited, significant future research is required in optimal placement methods that maintain QoS at minimal cost [8]. Such work must be done in conjunction with nascent work on the coordinated charging of electric vehicles [9]–[11].

B. Power System Assessment

EVs are fundamentally a part of the electrical energy system as EVs connect to the grid to charge. Specifically, as vehicles charge, they place an energy demand requirement that can be studied in terms of both energy as well as instantaneous power withdrawals [4]. Depending on the driving pattern of Abu Dhabi's drivers, the charging behaviour will differ. This indicates that the electrical system plays an essential role in the wide adoption of EVs as it represents the main source of energy for charging. It is critical to determine the feasibility of the distribution network to handle the wide adoption of EVs into the transportation system. The supporting infrastructure is therefore essential to be modeled and assessed in the technical feasibility study of EVs in Abu Dhabi. The extent of EVs impact on the local power supply will depend on the degree and density of their penetration, charging requirements as well as time of the day they are charged. Therefore, this example assessment has considered these three aspects impacting the power system by addressing the the 6 scenarios discussed in Section II-A.

Prior to proceeding, it is important to get an intuitive understanding of the relative size of EV charging power requirements relative to a home. Figure 8, shows the power requirement of a single home in San Francisco Bay with and without charging and demonstrates the associated power increase with changes in the charger type [4], [12], [13]. In all cases, EV charging represents a significant additional load on the house that does not have EV charging. San Francisco, however, has a very temperate climate and so has neither a high electrical heating or cooling requirement. Abu

Dhabi villas, however, are not only larger in size, but also rely heavily on air conditioning leading to higher electrical loads. According to the Abu Dhabi Regulation and Supervision Bureau, the average power draw of an Abu Dhabi home is approximately 11kW [12], [13].

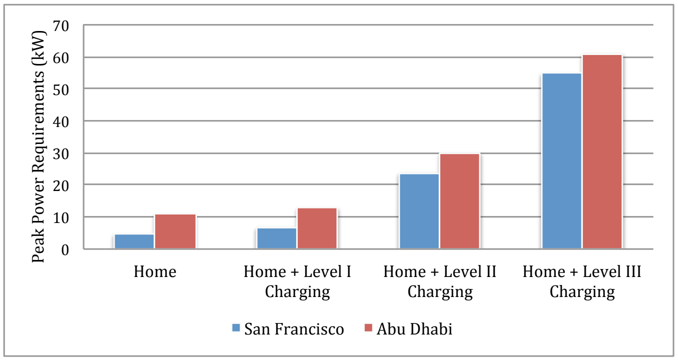

Figure 8: Peak Power Requirement of a Single Home in San Francisco Bay and Abu Dhabi With and Without EV Charging [4], [12], [13]

While average power consumption of a home is useful for gaining an intuitive understanding of the relative size of EV charging, it is not the basis upon which the electrical distribution system is designed, operated and maintained. Rather, because the grid needs to support all possible loads, the peak load consumption of a home is most important. To that effect, a large Abu Dhabi villa may have a peak load up to as high as 200-250kW [12], [13]. This peak power value is important relative to the ratings of transformers, feeders, and substations in the Abu Dhabi electrical distribution system.

With this intuitive understanding of charging power loads, the results from the charging results from the CMS can be better to understood. It is important to recognize that the Clean Mobility Simulator, like other traffic simulation tools, simulates traffic evolution from origin to destination and so does not capture any activity including charging before an origin or after a destination [7]. In order to overcome this challenge, the simulations were implemented as two sets of sets of electric vehicles. The first set leaves in the morning with a full charge while the second set leaves in the afternoon with a 50% initial state of charge. As a result, the simulations assume that the vehicles that had travelled in the morning had done so and expended 50% of their charge in the process without drawing on the grid for power. As the simulation results show, none of the morning trips expended sufficient battery charge so as to require morning charging. Subsequently, all charging occurred in the latter half of the day. As expected, in all cases, as EV penetration increases, so too does the total power demanded. The remainder of the section interprets and differentiates the results of the six simulation cases.

1) Limited Dense Charging System Design: The Limited Dense charging system design has the smallest charging system load curve at around 1MW for all three penetration rates. In absolute terms, 1MW comprises a very small portion of the Abu Dhabi generation capacity of 11 GWs [14]. Therefore, from an energy perspective, EVs do not present a major challenge. More interestingly, this charging system's load curve is characterized by saturation, which only becomes more prevalent with penetration rate. This saturation is due to the limitations in the number of chargers and their type and is best illustrated with a simple capacity calculation. Six charging stations each with 10 charging slots which consume at the Type II charger power of 19kW yields 1.14MW. Therefore, the charging station capacity becomes a type of system "bottleneck" where the impact on the power grid is the maximum possible but also generally decoupled from the vehicle dynamics in the transportation system. Although, this saturated and highly predictable load curve is desirable from a power utility perspective, it is entirely undesirable from a transportation system perspective in that it causes charging station queues and degraded quality of service. Recall from Section IV that the limited dense charging station design resulted in low QoS values especially at higher penetration rates.

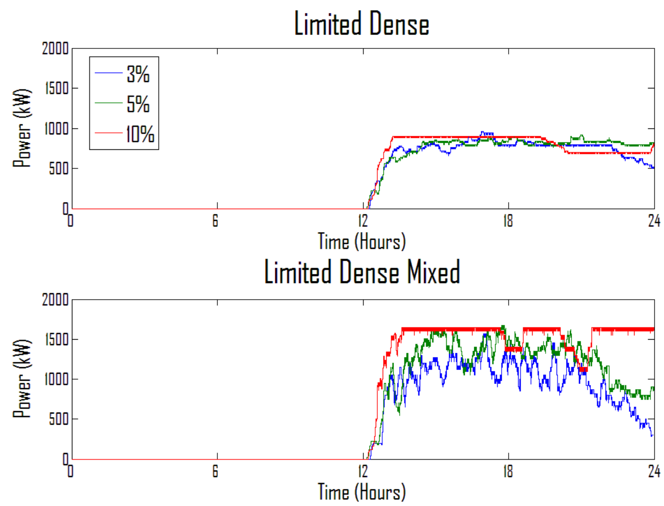

Figure 9: Charging System Load Curves for all 6 Simulation Cases

The corresponding line/transformer safety criterion values provide a similar understanding. As shown in Figure 10, the limited dense charging station design does not exceed transformer safety limits when 100 or 200kW of available capacity are assumed. Only in the case of 50kW of available power capacity does this charging station exceed the safety criterion; although it does so at the same level irrespective of penetration rate. Once again, the saturation of the charging station limits the power drawn to a highly predictable value.

2) Limited Dense Mixed Charging System Design: The Limited Dense Mixed charging station design has similar load curves to the limited dense case but with higher limits and greater variability. Although, the charging slots available are the same, the types of chargers differ. The Level III chargers are able to more quickly process any charging station queues and so the aggregate load curve is more variable than the limited dense charging station design. The replacement of

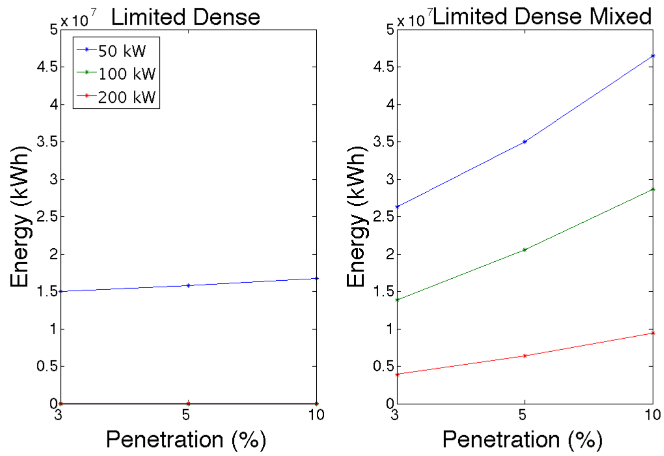

Figure 10: Safety Criterion Results

three Level II chargers with Level III chargers also increased the saturated maximum power from 1MW to 1.5 MW. As before, the saturation of chargers and the limiting maximum power gives an advantage to the power utilities because of the ease of predictability. However, as with the limited dense case, a degradation in the QoS follows.

The charging power variability in the limited dense mixed charging system provides a new operational challenge to power system utilities. Power utilities' main operational challenge is to maintain the balance of power consumed and generated [15], [16]. This task is easiest for well quantified, predictable, and slowly evolving loads. In contrast, the power drawn in this case is highly variable. Such a result suggests that power system utilities would have to use the power system's regulation services to automatically control generation in response. Such a solution is technically viable provided that the degree of variability is within the saturation limits of the planned regulation service [15]–[17]. The few hundred kWs of variability shown above is not likely to exceed any major technical limits. Nevertheless, regulation services are the most expensive form of power and their additional use can add an extra marginal cost for power utilities and their consumers [15].

As shown in Figure 10, the line safety criterion provides similar information for the limited dense mixed charging system design. In comparison to the limited dense charging system design, the inclusion of Type III chargers in the limited dense mixed charging system now requires lines and transformers to have greater available power capacity to avoid exceeding the safety limits regardless of whether there was 50, 100, or 200kW of available power capacity. As shown in Figure 9, the total energy exceeding the power limit has a positive slope with the EV penetration rate. This suggests that the EVs are not just consuming more power but they are also doing so at times when other vehicles are charging; adding to the times in which the lines are over their safety limits.

The implications of such results are significant. Installation of such a charging station design would naturally require careful thought as they are integrated into the power grid. One solution would be to upgrade the lines/transformers to which the charging station is connected and another would be to connect the charging station to a higher distribution system voltage [4], [18]–[20]. This would require a dedicated charging station transformer. Both solutions require significant capital expenditure, which may affect the ultimate viability of the envisioned EV adoption scenario.

C. *Intelligent Transportation System Assessment*

The AD DOT ITS [21] is a conceptual vision of a final implementation rather than a detailed fixed current design. Therefore, at such an early conceptual design stage in the systems engineering process, the document rightly does not contain the detailed component interfaces or functional interactions. A complete reverse engineering analysis of the AD DOT ITS only lead to a very partial MDM. This means that the ITS design is still fluid enough that these detailed interfaces and interactions have not yet calcified thus facilitating incorporation of functionality and its associated modules and components. The completed sections did highlight many-to-one type relationships existed between the function, form and stakeholder domains potentially causing unnecessary system coupling and complexity at a later stage in the systems engineering process. Managing the relationships between functions, components and stakeholders can become a particularly challenging task.

V. Discussion: The Need for an Intelligent Transportation-Energy System

The integrated assessment results from the previous section suggest that traffic and charging functionality must be considered holistically within an integrated operations management environment. Consider the concrete example of an EV taxi or bus operators. It may wish to dispatch its EVs along certain routes at certain times. However, this decision may depend on the existing charging station queues in the city. These queues in turn depend on the presence or absence of coordinated charging functions which may limit charging loads to the electrical grid. Finally, the local electric utility may even incentivize this EV operator to implement a "vehicle-to-grid" scheme to stabilize variability in grid conditions. Therefore, rather than an intelligent transportation system, it seems that electric vehicles require an Intelligent Transportation-Energy Systems (ITES) in recognition of dual coordination role. For the remainder of this discussion, an ITES is taken to be a system with the combined functionality of an ITS and an energy/distribution management system. The nature of such a system is now discussed from the perspective functional requirements, stakeholders and finally components.

A. *Integration of Functional Requirements*

The integration of EVs adds new functionalities that are distributed across the potential program packages of a new ITES. Although the AD DOT ITS strategic vision highlights the importance of a low carbon economy as one of its top-level goals, energy management did not explicitly appear within the set of functional requirements. In contrast, Figure 11 proposes a new set of functional requirements (FRs) to be part of the ITS which will help facilitate the management of EVs. These functional requirements include the management and operation of charging station as well as EVs.

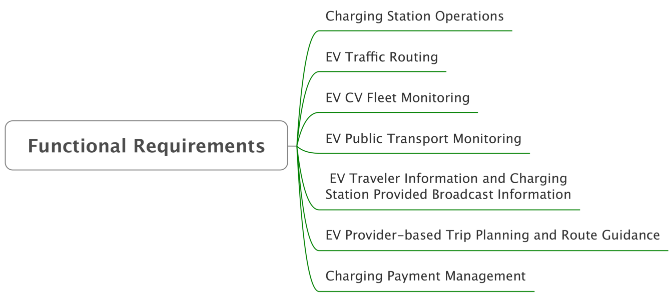

Figure 11: Integration of EVs as a Functional Requirement in Abu Dhabi's ITES [2]

B. Integration of Stakeholders

The newly proposed ITES also adds new stakeholders into the system. These include charging station operators and electric vehicle drivers. Figure 12 demonstrates the additional roles and responsibilities of this enhanced group of stakeholders. Most interestingly, as EVs begin to couple the transportation and the power system, there will be additional responsibilities on electric utilities such as the Abu Dhabi Distribution Company (ADDC). Naturally, coordinated real-time operations management between the ADDOT and ADDC would present an interesting challenge of jurisdiction and cooperation.

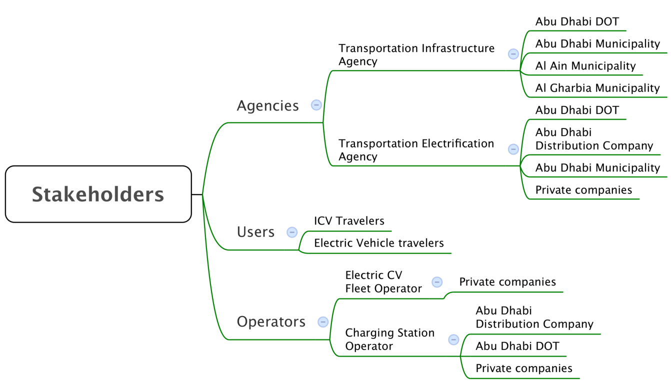

Figure 12: Integration of EVs as New Stakeholders in Abu Dhabi's ITES [2]

C. Integration of Components

The ITES would also call for a new set of management systems and technology elements to facilitate the adoption of EVs. Given that EVs have a number of potential use cases including: corporate fleets, public transportation and private users, Figure 13 demonstrates the new components which may require potential integration. For example, charging stations can be available in taxi stands or parks. Each of these charging stations can be used for public transport or private users. Also, if a corporate vehicle fleet were to decide to switch to electric transportation, an EV management system will be required to do so. Another major change in the inventory list proposed is the classification of ICV and EV drivers. Each of these drivers will require a different set of services and therefore should be classified according to the vehicle type.

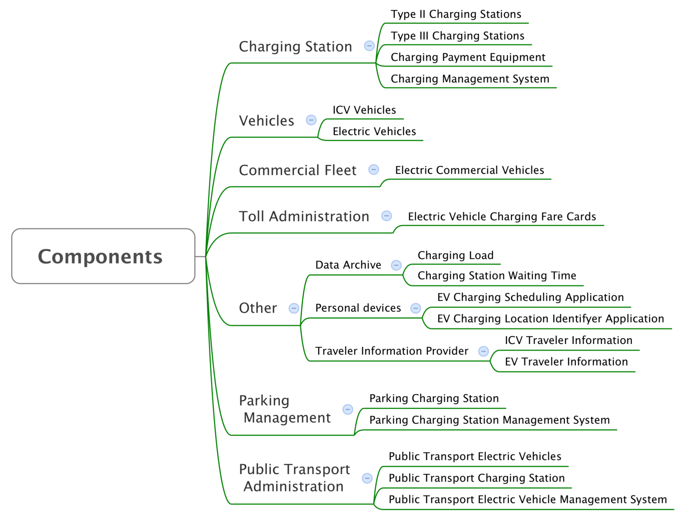

Figure 13: Integration of EVs as New Components in Abu Dhabi's ITES [2]

VI. Conclusion & Future Work

This paper has presented the first full scale technical feasibility assessment of electric vehicles for the city of Abu Dhabi. The assessment has provided a thorough assessment of six EV penetration scenarios based upon three penetration rates and two charging system designs. It showed clearly that the EV brings about a transportation-energy nexus in which negative impacts can be shifted from the transportation system to the power system and vice versa. Undesirable charging queues provide stable electric power loads to a utility while uncoordinated charging can cause electric vehicles to behave like variable energy resources. The mitigation of these averse impacts could have significant economic impacts outside the scope of the EV manufacturer that can ultimately impair the EV adoption trajectory.

The conclusions of the assessments results are most easily summarized by Figure 14. The assessment results showed that the design of the charging system itself is highly influential in either amplifying or mitigating the impacts of the EV integration. This is a multi-variable design space and unrationalized decisions can easily have unintended consequences on the combined transportation-energy nexus. The technical implications on the power system and transportation system for the five previously mentioned statistics. On the transportation side, low QoS which is also evidenced by low power variability and high maximum energy of load curves, can significantly impair long term EV adoption and reduce the revenue of the transportation services that choose to use electric vehicles. On the power system side, high max power could cause significant capital expenditures in upgrading lines and transformers. Meanwhile, high power variability will require

Technical Challenge	High Max. Energy	High Max. Power	High Power Variability	Low Min.Energy	Low Power Variability
Technical Implications on Power System	None. Small in comparison to generation capacity	Overloaded lines & transformers	1) System wide need for generator ramping capabilities. Appears as flexible generation, synchronized reserves, & regulation services 2) System wide need for improved charging load forecasting	None	None.
Technical Implications on Transportation System	Suggests long charging queues and reduced QoS.	None	None	Under-utilized charging station.	Suggests long charging queues and reduced QoS.
Economic Implications	1) Impaired EV adoption. 2) Reduced transportation service revenues	Significant capital expenditure on line & transformer upgrades	1) System wide increase in the marginal cost of electricity. 2) Potential need for capital investments into flexible generation and automatic generation control	1) Poor ROI. 2) Weak financial rationale for charging station	1) Impaired EV adoption. 2) Reduced transportation service revenues
Mitigating Charging System Design Heuristic	1) Optimize the scope of the EV use case 2) Expand number of charging stations w/ optimal placement algorithms 3) Balance increased costs with potential revenue losses	1) Coordinated charging strategy 2) Optimal placement algorithms 3) Systematic preference for Type II chargers 4) Reduce number of charging station slots	1) Coordinated charging strategy 2) Type III chargers as chargers of last resort. 3) Optimal placement of Type III chargers for high utilization	Optimal placement algorithms for charging stations	1) Expand number of charging stations w/ optimal placement algorithms 2) Balance increased costs with potential revenue losses

Figure 14: Charging System Design Heuristics for Mitigation of Impacts to Transportation-Energy Nexus [2]

the use of generation with significant ramping capabilities: flexible generation, synchronized reserves, and automatically controlled regulation services. All of these lead to a system wide increase in the marginal price of electricity. If there is insufficient flexibility in the generation fleet, then EV integration could potentially require further capital expenditures.

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References

[1] R. A. Junaibi and A. M. Farid, "A Method for the Technical Feasibility Assessment of Electrical Vehicle Penetration," in *7th Annual IEEE Systems Conference*, Orlando, FL, United states, 2013, pp. 1–6.

[2] R. A. Junaibi, "Technical Feasibility Assessment of Electric Vehicles in Abu Dhabi," Master's thesis, Masdar Institute of Science and Technology, 2013.

[3] R. Al Junaibi, A. Viswanath, and A. M. Farid, "An Integrated Method to Assess Infrastructure Technical Readiness for EV Penetration," *submitted to: IEEE Systems Journal*, pp. 1–10, 2013.

[4] J. G. Kassakian, R. Schmalensee, G. Desgroseilliers, T. D. Heidel, K. Afridi, A. M. Farid, J. M. Grochow, W. W. Hogan, H. D. Jacoby, J. L. Kirtley, H. G. Michaels, I. Perez-Arriaga, D. J. Perreault, N. L. Rose, G. L. Wilson, N. Abudaldah, M. Chen, P. E. Donohoo, S. J. Gunter, P. J. Kwok, V. A. Sakhrani, J. Wang, A. Whitaker, X. L. Yap, R. Y. Zhang, and M. I. of Technology, *The Future of the Electric Grid: An Interdisciplinary MIT Study*. Cambridge, MA: MIT Press, 2011.

[5] S. D. Eppinger and T. R. Browning, *Design structure matrix methods and applications*. Cambridge, Mass.: MIT Press, 2012.

[6] M. A. Hadhrami, A. Viswanath, R. A. Junaibi, A. M. Farid, and S. Sgouridis, "Evaluation of Electric Vehicle Adoption Potential in Abu Dhabi," Masdar Institute of Science and Technology, Abu Dhabi, UAE, Tech. Rep., 2013.

[7] T. Sonoda, K. Kawaguchi, Y. Kamino, Y. Koyanagi, H. Ogawa, and H. Ono, "Environment-Conscious Urban Design Simulator "Clean Mobility Simulator" - Traffic Simulator that Includes Electric Vehicles," *Mitsubishi Heavy Industries Technical Review*, vol. 49, no. 1, pp. 78–83, 2012.

[8] L. Gan, U. Topcu, and S. Low, "Optimal decentralized protocol for electric vehicle charging," in *IEEE Conference on Decision and Control and European Control Conference*. Ieee, 2011, pp. 5798–5804.

[9] M. Ahman, "Government policy and the development of electric vehicles in Japan," *Energy Policy*, vol. 34, no. 4, pp. 433–443, Mar. 2006.

[10] W. Kempton and J. Tomić, "Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy," *Journal of Power Sources*, vol. 144, no. 1, pp. 280–294, Jun. 2005.

[11] H. Lund and W. Kempton, "Integration of renewable energy into the transport and electricity sectors through V2G," *Energy Policy*, vol. 36, no. 9, pp. 3578–3587, Sep. 2008.

[12] Anonymous, "Power Distribution Network Planning Criteria and Design Philosophy," Abu Dhabi Distribution Company, Power Network Development Department Asset Management Directorate, Abu Dhabi, UAE, Tech. Rep. January, 2007.

[13] ——, "Report Consumption Water and Electricity," Regulation and Supervision Bureau, Abu Dhabi, UAE, Tech. Rep. 1999, 2007.

[14] ——, "The Abu Dhabi Economic Vision 2030," Abu Dhabi, UAE, Tech. Rep., 2008.

[15] A. Gomez Exposito, A. J. Conejo, and C. Canizares, *Electric energy systems: analysis and operation*. Boca Raton, Fla: CRC, 2008, vol. The electr, no. Recommended.

[16] P. Schavemaker, L. Van der Sluis, and Books24x7 Inc., *Electrical power system essentials*. Chichester, England ; Hoboken, NJ: Wiley, 2008.

[17] A. J. Wood and B. F. Wollenberg, *Power generation, operation, and control*, 2nd ed. New York: J. Wiley & Sons, 1996, vol. 2, no. 2.

[18] W. Su, H. Rahimi-eichi, W. Zeng, and M.-y. Chow, "A Survey on the Electrification of Transportation in a Smart Grid Environment," *IEEE Transactions on Industrial Informatics*, vol. 8, no. 1, pp. 1–10, 2012.

[19] S. Brown, D. Pyke, and P. Steenhof, "Electric vehicles : The role and importance of standards in an emerging market," *Energy Policy*, vol. 38, no. 7, pp. 3797–3806, 2010.

[20] Z. Li and M. Ouyang, "The pricing of charging for electric vehicles in China—Dilemma and solution," *Energy*, vol. 36, no. 9, pp. 5765–5778, Sep. 2011.

[21] ADDOT-Anonymous, "Abu Dhabi Intelligent Transportation Systems: Strategy Architecture and Implementation Action Plan 2010- 2030," Abu Dhabi Department of Transportation, Abu Dhabi, Tech. Rep. 3, 2011.