Peer-to-Peer Energy Trading and Grid Control Communications Solutions' Feasibility Assessment based on Key Performance Indicators

Jussi Haapola[1], Samad Ali[1], Charalampos Kalalas[3], Juho Markkula[1], Nandana Rajatheva[1], Ari Pouttu[1],
José Manuel Martín Rapún[2], Iván Lalaguna[2], Francisco Vazquez-Gallego[3], Jesus Alonso-Zarate[3], Geert Deconinck[4],
Hamada Almasalma[4], Jianzhong Wu[5], Chenghua Zhang[5], Eloisa Porras Muñoz[6], Francisco David Gallego[7]
[1]Centre for Wireless Communications, University of Oulu | [2]Inycom, Spain | [6]Endesa S.A., Spain
[3]Centre Tecnològic de Telecomunicacions de Catalunya, Spain | [4]ESAT-ELECTA, KU Leuven, Belgium
[5]Cardiff University, United Kingdom | [7]Regenera Levante, Murcia, Spain

***Abstract*—Selection of the most appropriate communications technology for a smart grid application is far from trivial. We propose such a feasibility assessment starting from identification of key performance indicators (KPIs) required for peer-to-peer (P2P) energy trading and grid control operations from a communications perspective. A set of cross-disciplinary KPIs, both quantitative and qualitative, are considered from communications, power, business, actor involvement, financial, and demand side management categories. They serve as a general baseline for use cases, as there have been few previous works attempting to capture the essential features of P2P smart grid operations. The KPIs are briefly identified along with their relations to P2P energy trading and grid control. A straightforward comparison of the quantitative and qualitative KPIs' impact on technology selection is not feasible. This paper addresses the comparison with: 1) a prioritization of the KPIs using the analytic hierarchy process; 2) a comparison of a number of technology solutions evaluated in our previous works against the KPIs' requirements; and 3) total feasibility evaluation of the solutions against selected KPIs. The prioritization of KPIs shows that latency, reliability, security, scalability, robustness, costs of ICT devices, and costs of ICT deployment are the most important KPIs in enabling P2P energy trading and grid control. Moreover, the technology feasibility assessment enables identification of the most suitable candidates for a smart grid application.**

I. Introduction

The current electric power system has a structure enabling one-way flow of electricity from bulk generation units to energy consumers. In the advent of emerging penetration of renewable energy sources, electric vehicles, and customer energy flexibility down to household and even to individual electrical load level, solutions that empower the consumers are of essence. The ageing power grid system lacks the required technology and flexibility to integrate distributed generation elements. Advanced control and information and communication technologies (ICT) are hence required in the power grid to include such elements, creating the Smart Grid [1]. Adding renewable energy resources opens up new business opportunities, such as peer-to-peer (P2P) energy trading. P2P energy trading consists of the exchange of surplus electricity between prosumers of energy in the smart grid with the help of innovative business models and advanced ICT technologies.

The key contributions of this paper are the identification and the prioritization of the most relevant key performance indicators (KPIs) with respect to P2P energy trading and grid control communications using the analytic hierarchy process (AHP), and the communications technology feasibility assessment against the most important KPIs. We propose a set of cross-disciplinary KPIs and a feasibility assessment of communications technologies against those KPIs. The considered candidate wireless technologies [2] include license-free bands solutions (e.g., IEEE 802.15.4 and WiFi), new internet-of-things (IoT) specific technologies such as LoRaWAN and IEEE 802.15.4-2015 LECIM, and cellular communication systems and their evolved versions for machine-to-machine (M2M) communications [3]. Smart grids involve a wide range of applications with various communications requirements; some with demanding quality of service requirements of very low latency and high reliability [4].

The rest of the paper is organized as follows. Section II proposes and briefly elaborates the KPIs. Section III briefly introduces the AHP and derives the relative priorities of the KPIs. Section IV proposes technology feasibility assessment against the most important KPIs and shows the results. Section V concludes the paper.

II. Key Performance Indicators

P2P energy trading and grid control KPIs are categorized in domains shown in Fig. 1. Due to page restrictions, we provide only a brief definition of each KPI. More detailed description can be found from P2P-SmarTest Deliverable D3.2 [5].

A. Communications domain

1) Data Delivery Rate: refers to the required successfully delivered data to an entity over a given transmission time.

2) Distance: refers to the feasible physical separation of two entities for smart grid communications.

3) Latency: refers to the (end-to-end) time elapsed from the moment a data packet is generated at the transmitter side until it can be properly decoded on the intended receiver side. Latency in smart grid communications is divided into regular, emergency, and protection circuitry cases.

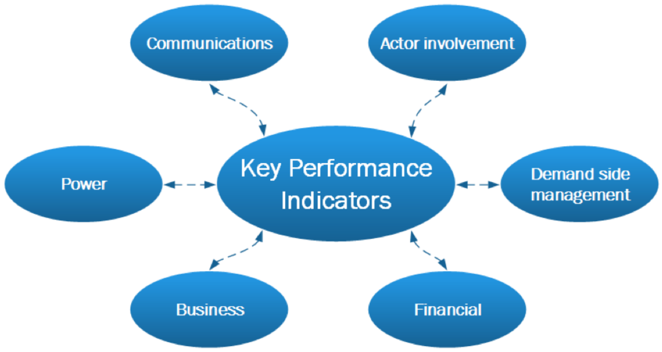

Fig. 1: Categorization of key performance indicator domains.

4) Reliability: refers to the ability of a communications link to consistently deliver data. Typically, 98% delivery ratio is required, and it can be up to 99.99% [4]. In demand response (DR), reliability of $> 99.5\%$ [6] is expected.

5) Energy Efficiency: refers to the useful power output divided by the total electrical power consumed, and constitutes an essential concern in communications [7].

6) Spectrum Efficiency: refers to the information rate transmitted over a given bandwidth.

7) Number of Supported Users: refers to the number of smart grid entities that can be supported by a single coordinator device or data collection point. Due to smart meter on/off behavior it is important to design proper network access mechanisms to provide connectivity to the entities [8].

8) Scalability: refers to the ability of the communication network to adjust its dimensions to accommodate large number of users and be flexible to add more users.

9) Trust (Security): refers to data integrity and trust relationship required regardless of the communication medium. Security is the ability of the system to combat cyber-attacks and threats on the network. Since in P2P-enabled smart grids cyber-attacks can degrade the system performance and cause severe damage, security is of very high importance [9].

10) Data Transmission Frequency: refer to the time instants when data should be communicated in smart grids and they depend on the application. Monitoring and metering information have periodic data traffic patterns and modest inter-arrival times whereas control and protection functions are event-based with short inter-arrival times. P2P energy trading and grid control is mostly monitoring and metering, while at times the data can be event driven and have high bursts [10], [11], [12].

11) Computing Capabilities: represents the capability of a communication entity in processing the measured and communicated data.

12) Information Storage Capabilities: refers to memory in devices and it helps in cases of failure of the communication system. Combined with computing capabilities, it could provide local intelligence which is an enabler of P2P actions.

13) Flexible Communications, Ports and Protocols: refer to the compatibility of communication equipment with wide range of devices installed in a smart grid.

14) Size: refers to the communication equipment dimensions as there may be limited room for metering equipment.

15) Openness: is an attribute related to the availability of information about the communication device and the ability to make changes for it. Since in smart grids new applications, such as P2P functionalities could be added, it is very important for devices to be able to be updated.

16) Robustness: refers to communication hardware, which should withstand challenging ambient conditions and continue performing its tasks for several years. The number of particular hardware vendors is a feasible measure of robustness.

B. Power domain

1) Share of RES/DER: (renewable energy sources / distributed energy resources) refers to the capability of a technology to support RES and DER. With RES we refer to wind and solar generation connected to distribution networks whereas DER refers to both renewable and non-renewable small and medium distributed resources connected to a distribution grid.

2) Share of EV/Storage: refers to electric vehicles (EV) and the batteries represent new loads connected to the low voltage network, originally planned without considering these active players [13]. These new connections impose additional requirements and patterns for communications and increases the complexity of the distribution grid control and operation.

C. Business domain

1) Number of Market Players and Tariff Schemes: The number of market players is one of the KPIs that affects the P2P energy trading communications. Number of tariff schemes offered to consumers in P2P energy trading business models have effect on the amount of exchanged data and hence the communication system.

D. Actor Involvement domain

1) Degree/Easiness to which Consumers can become Prosumers: There will be more communication among prosumers compared with traditional consumers in the system. This indicator can describe which consumers can become prosumers, and as a result, have the potential to require more communications than others.

2) Controlling – Home Automation (HA): should support demand response actions. The type of the demand response program defines the amount of the data delivered between the HA and the energy retailer.

E. Financial domain

1) Amount of Investment for ICT devices: refers to communications hardware, possible subscription fees, and required servers of smart grid communications entities.

2) Amount of investment needed to install ICT: refers to the personnel training, labor, and maintenance costs related to the items mentioned in the previous KPI and grows significantly for every new type of technology.

F. Demand Side Management (DSM) domain

1) Demand Side Flexibility: refers to ability of a prosumer to select between various DR programs. There will be no significant impact on communications as long as the selected DR criteria can be satisfied.

TABLE I: Results of AHP

KPI	AHP weights
Latency, protection circuitry	11.7%
Latency, emergency case	10.5%
Reliability	9.9%
Trust (Security)	6.4%
Robustness	5.4%
Amount of investment for ICT devices	5.3%
Number of supported users	4.8%
Scalability	4.5%
Amount of investment needed to install ICT	4.1%
Communication time frequency	3.0%
Latency, normal case	2.9%
Openness	2.9%
Number of market players and tariff schemes	2.7%
Distance	2.6%
Computing capabilities	2.5%
Degree/easiness to which consumers can become prosumers	2.3%
Information storage capabilities	2.2%
Controlling: home automation	1.9%
Flexible communications	1.8%
Size	1.7%
Power Efficiency	1.6%
Demand-side flexibility	1.5%
Data delivery rate	1.4%
Spectrum Efficiency	1.4%
Share of RES/DER	0.9%
Share of EV + Storage	0.9%
Share of DMS	0.8%
Potential for time shift	0.8%

2) Share of DSM: evaluates the percentage of loads to be shifted or disconnected in order to face a congestion in the grid due to energy demand peaks. The KPI provides an estimation of the potential demand flexibility of a "consumer peer" to be included in a demand bids of the P2P trading algorithm.

3) Potential for Time Shift: refers to the time slots in which a number of loads can be shifted or disconnected. The KPI is relevant for P2P energy trading communications because it has to be conveyed in the demand bids that are exchanged among peers by the P2P trading algorithms.

III. KPI Prioritization

KPI prioritization provides a method for understanding the most important quantitative and qualitative KPIs in P2P energy trading and grid control communications. The analytic hierarchy process (AHP) [14] is applied here as it enables the relative comparison of arbitrary objects with one another and a mathematically formulated method of addressing the problem. Even though some of the items in the prioritization process can be correlated, this correlation is not a problem in AHP. The AHP does not require uncorrelated objects [14] since it is not an optimization tool, but rather a tool to understand relative weights between the objects.

A. Analytic hierarchy process (AHP)

A number of methods have been developed to address pair-wise comparisons of the alternatives and for solving multi-criteria decision-making (MCDM) [14] between finite alternatives. AHP is a very popular approach to MCDM that involves qualitative data. The method uses a reciprocal decision matrix obtained by pair-wise comparisons so that the information is given in a linguistic form [15]. Rather than prescribing a "correct" decision, the AHP helps in determining one. The AHP provides a comprehensive and rational framework for structuring a problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions. There are three main levels of hierarchy in the AHP: the overall goal on the top, the available alternatives at the bottom, and the (sub)criteria in the middle. The middle part containing the (sub)criteria can span over an arbitrary depth of levels of hierarchy itself. The compared alternatives and criteria (objects) form a linguistic (subjective) scale for making a comparison. The linguistic scale is characterized as one object being from "extremely less important" to "extremely more important" than another object. This linguistic scale must be transitive [16] i.e., if KPI#1 is "moderately more important" than KPI#2 and KPI#2 is "strongly more important" than KPI#3, then KPI#1 must be more than "strongly more important" than KPI#3. This can be monitored by a consistency ratio (CR) upon solving the AHP using the eigenvector method. The linguistic scale is then translated into a numerical format, e.g., by using the Saaty scale [17].

To achieve prioritization, a priority vector is derived from the numerical pair-wise comparisons. The two most common prioritization methods are the eigenvalue method and the logarithmic least squares method [17]. The eigenvalue method is applied here, where the principal eigenvector of the numerical pair-wise comparison matrix $A = (a_{ij})_{n\times n}$, $a_{ij} = f(d_{ij}), i, j \in [1, n]$ is the desired priority vector w. The w can be obtained by solving the linear system

$$Aw = \lambda w, \qquad e^T w = 1, \tag{1}$$

where λ is the eigenvalue of matrix A [17]. Solving the linear system of Eq. (1) provides a matrix of eigenvectors and a diagonal matrix of eigenvalues, where the largest real eigenvalue corresponds to the principal eigenvalue. The principal eigenvector is then the column corresponding to the column of the principal eigenvalue. The w is then normalized by the sum of its elements so that the normalized sum equals to 1. The normalized priority vector then provides the relative importance of each alternative.

B. Analytic hierarchy process of the KPIs

A flat AHP structure is used to carry out the pair-wise comparisons as the relative weights of Fig. 1 categories are not known i.e., all the KPIs (alternatives) are compared with one another. The relative weight of each KPI is the goal of the AHP and the KPIs are the alternatives. Pair-wise comparisons were carried out by the Partners of P2P-SmarTest project, and from the communications perspective i.e., "if we need to communicate information, how does KPI#n relate to KPI#m?". Furthermore, as the interest is in P2P energy trading and grid control: "is KPI#n more/less important than KPI#m?" Bearing the previous factors in mind and using the 17-step linguistic set and its corresponding numerical values [17], a pair-wise comparison matrix was constructed for each contribution and the linear system of Eq. (1) was solved. This was done to confirm the consistency of all contributions. The consistency of pair-wise comparisons can be observed from calculation of the consistency index (CI)

$$CI = \frac{\lambda_{max} - k}{k - 1}, \tag{2}$$

where λ_{max} is the largest eigenvalue of the comparison matrix and k is size of the matrix. The consistency ratio (CR) is the measure indicating if the inconsistency is acceptable in the matrix. The CR should be less than 0.1 for pair-wise comparisons to be consistent and $CR = \frac{CI}{RI}$, where RI is the random consistency index for a matrix the size of n. Here with $n = 28$, a value of 1.577 was used for the RI.

After observing that the individual pair-wise comparison matrices were reasonably consistent, an average pair-wise comparison matrix was produced using a pure arithmetic average over each element of the matrix. The resulting $[28\times28]$ element matrix was inspected element by element and each element with a value of 1 or higher was rounded to the nearest integer value. Finally, as the pair-wise comparison matrix must be reciprocal, the reciprocal element of each rounded element was recomputed to be the reciprocal of the just rounded value. Lastly, the obtained averaged and reciprocal pair-wise comparison matrix was solved using Eq. (1). Solving the matrix yields a consistency ratio of 0.0677, which is significantly less than the CR limit proposed by Saaty.

The relative weight vector of KPIs is illustrated in Table I. Latency in emergency and critical cases, reliability, trust, robustness, investment needed, installation costs, number of supported users, and scalability are generally the most important KPIs. One must note that not all the KPIs are applicable in all P2P energy trading and grid control scenarios.

IV. Technology feasibility against KPIs

In the P2P-SmarTest project we have simulated and analyzed multiple communications technologies relevant for smart grid applications. The simulations were carried out using NS-3 and Riverbed Performance Modeler (former Opnet) simulators, the simulators' consistency was benchmarked, and initial performance results were provided in [18]. We consider technology feasibility against KPIs in three applications:

1) AMR type energy trading: 98% reliability, 10 *min* data interval, maximise no. supported users, < 60 s latency;
2) DR type energy trading: 99.5% reliability, 4 s uplink/downlink data interval, maximise no.supported users and, < 1 s latency;
3) grid control: $> 99.5\%$ reliability, bursty high probability (50%) a of grid control event per 1 *ms*, 50 *ms* maximum latency.

Not all of the KPIs of Table I are relevant in all applications. For example, we argue that in P2P DR 'latency, protection circuitry' and 'latency, emergency case' are not relevant and thus, 'Reliability', 'Trust', and 'Robustness', become the most important KPIs from the communications point of view. In distributed voltage control, the results show 'Latency, emergency case', 'Reliability' and 'Security' being the most important factors that should be taken into account in design of communication system for this application. In both cases there are both quantitative and qualitative KPIs. To determine the KPI weighted suitability of a communications technologies for a given application, one could construct for example a single compound metric as in [19] to evaluate which one prevails. In this paper, we consider the KPIs 'Reliability', 'Trust', 'Robustness', Cost ('Amount of investment for ICT devices' and 'Amount of investment needed to install ICT'), and 'Number of supported users' in all the three applications. In energy trading we also consider 'Latency, normal case' and in grid control 'Latency, emergency case' as an evaluated KPI.

For application 1 we have simulated the IEEE 802.15.4-2015 LECIM network and LoRaWAN network equipped with an LTE capable coordinator node (LTE – LoRaWAN). These technologies do not scale up in DR scenarios due to regulatory and data volume issues. The application 2 technologies: Cat 4 LTE, ad hoc LTE [20] (similar to 3GPP release 14 cellular V2X mode 4), IEEE 802.11n, IEEE 802.15.4-2015 with LTE capable coordinator (LTE – IEEE 802.15.4), and IEEE 802.11n with LTE capable coordinator (LTE – IEEE 802.11n) can all manage also application 1 but cannot exploit very long link distances. For application 3 we have considered Cat 4 LTE, LTE with optimized random access channel (RACH), and LTE enhanced with device-to-device communications.

A. Feasibility point evaluation

We evaluate the feasibility points of the communications solutions with the six KPIs in all applications in the following way. In the case a solution fulfils a 'Latency' or 'Reliability' KPI, it receives full feasibility points as indicated by the KPI weight in Table I. If not, formula $\frac{KPI_{target}}{KPI_{achieved}} KPI_{weight}$ is used for latency (normal/emergency cases), and the formula $\frac{KPI_{achieved}}{KPI_{target}} KPI_{weight}$ is used for the reliability, where KPI_{target} is the KPI performance requirement, $KPI_{achieved}$ is the communications solution achieved performance, and KPI_{target} is the AHP weight of the KPI in Table I. The 'Number of supported users' KPI utilizes the latter formula substituting KPI_{target} with the solution of highest number of supported users in an application. The 'Robustness' KPI is evaluated by the maturity of the technology in terms of number of vendors: full feasibility points if more than six available vendors, $0.8 KPI_{weight}$ if more than two vendors, $0.6 KPI_{weight}$ if only one or two vendor(s). For 'Security' all the solutions are capable of key exchange mechanims: LTE-based solutions get full feasibility points due to their interference readiness, multi-frequency or DSSS solutions get $0.9 KPI_{weight}$, and single-channel solutions $0.8 KPI_{weight}$. In multi-technology solutions, the most unsecure technology defines the performance value. For the Cost assessment, we consider a practical network deployment scenario where a number of smart meters is installed within a suburban area of 5 km^2 with a node density of 1000 smart meters/km^2. Then, for each proposed solution, we carry out an evaluation on the needed coordinator devices and LTE user equipment needed for subscription purposes. In addition we consider the cost of all communications devices, coordinator devices, personnel for training and maintenance, development and subscription. We target a 20-year life cycle

TABLE II: Technology Feasibility against Key Performance Indicators

	Solution	Quantitative KPIs			Qualitative KPIs			Total feasibility
		Latency	**Reliability**	**No. supported users**	**Robustness**	**Security**	**Cost**	
AMR	IEEE 802.15.4 LECIM	normal 2.9%	9.9%	4.8%	3.24%	5.76%	9.4%	**36%**
	LTE – LoRaWAN			0.235%	4.32%		8.98%	**32.01%**
DR	LTE Cat. 4	normal 2.9%	9.9%	2.478%	5.4%	6.4%	1.2%	**28.28%**
	LTE with ad hoc enhancement			1.239%	4.32%			**25.96%**
	IEEE 802.11n			2.139%	5.4%	5.76%	9.4%	**35.50%**
	LTE – IEEE 802.15.4			1.487%			8.62%	**34.07%**
	LTE – IEEE 802.11n			4.8%			9.11%	**37.87%**
Grid control	LTE Cat. 4	emg. 7.292%	9.9%	2.566%	5.4%	6.4%	9.4%	**41.60%**
	LTE – RACH optimized	emg. 6.646%		4.8%				**42.55%**
	LTE with D2D enhancement	emg. 10.5%		3.029%	4.32%		9.37%	**43.52%**

and derive per-month, per-smart meter costs. Based on these network dimensioning considerations, we calculate the total deployment and operations cost for each solution in the applications 1-3. Then we normalize the resulting cost per technology over the lowest achieved cost for AMR, DR, and grid control applications, respectively, and we multiply with the corresponding AHP weight (investment+installation= 9.4%).

The Table II presents the obtained feasibility points in percentages. As only limited set of KPIs were addressed the maximum points would be 38.8% for AMR and DR, and 46.4% for grid control. Direct comparison between the applications is not meaningful due to qualitative KPI normalization in each application. The results show that no solution obtains maximum total feasibility, but IEEE 802.15.4 LECIM, LTE – IEEE 802.11n, and LTE with D2D enhancement obtain the highest total feasibility in applications 1 to 3, respectively.

V. Conclusion

This paper proposed a novel approach to assess communications technologies feasibility in P2P energy trading and grid control smart grid communications based on KPIs. 28 KPIs were identified and briefly elaborated from six smart grid domains and the KPIs were prioritized by applying the analytic hierarchy process, which was described in detail. Ten communications technology solutions: two for AMR, five for DR, and three for grid control applications performances were evaluated with respect to the six highest priority KPIs requirements. The paper further proposed a feasibility evaluation of each communications solution in the related applications with respect to the KPIs and identified the best candidates.

VI. ACKNOWLEDGMENT

This paper describes work undertaken in the context of the P2P-SMARTEST project, Peer to Peer Smart Energy Distribution Networks (http://www.p2psmartest-h2020.eu/), an Innovation Action funded by the H2020 Programme, contract number 646469, reported in [5], [18], and Deliverable D3.4.

References

[1] H. Farhangi, "The path of the smart grid," *IEEE Power and Energy Magazine*, vol. 84, no. 1, pp. 18–28, January 2010.

[2] Q.-D. Ho, Y. Gao, and T. Le-Ngoc, "Challenges and research opportunities in wireless communication networks for smart grid," *IEEE Wireless Communications*, vol. 20, no. 3, pp. 89–95, 2013.

[3] A. Rico-Alvarino, M. Vajapeyam, H. Xu, X. Wang, Y. Blankenship, J. Bergman, T. Tirronen, and E. Yavuz, "An overview of 3gpp enhancements on machine to machine communications," *IEEE Communications Magazine*, vol. 54, no. 6, pp. 14–21, June 2016.

[4] M. Kuzlu, M. Pipattanasomporn, and S. Rahman, "Communication network requirements for major smart grid applications in han, nan and wan," *Computer Networks*, vol. 67, pp. 74–88, 2014.

[5] Deliverable D3.2, "Key performance indicators for p2p energy trading communications," Peer to Peer Smart Energy Distribution Networks (P2P-SmarTest), Tech. Rep., 2016. [Online]. Available: http://www.p2psmartest-h2020.eu/deliverables

[6] L. Zheng, N. Lu, and L. Cai, "Reliable wireless communication networks for demand response control," *Smart Grid, IEEE Transactions on*, vol. 4, no. 1, pp. 133–140, March 2013.

[7] D. Feng, C. Jiang, G. Lim, L. J. Cimini, G. Feng, and G. Y. Li, "A survey of energy-efficient wireless communications," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 167–178, 2013.

[8] J. J. Nielsen, G. C. Madueño, N. K. Pratas, R. B. Sørensen, C. Stefanovic, and P. Popovski, "What can wireless cellular technologies do about the upcoming smart metering traffic?" *IEEE Communications Magazine*, vol. 53, no. 9, pp. 41–47, 2015.

[9] Y. Yan, Y. Qian, H. Sharif, and D. Tipper, "A survey on cyber security for smart grid communications," *Communications Surveys & Tutorials, IEEE*, vol. 14, no. 4, pp. 998–1010, 2012.

[10] C. Kalalas, F. Vazquez-Gallego, and J. Alonso-Zarate, "Handling mission-critical communication in smart grid distribution automation services through lte," in *Smart Grid Communications (SmartGridComm), 2016 IEEE International Conference on*. IEEE, 2016.

[11] B. G. Gebremedhin, J. Haapola, and J. Iinatti, "Performance evaluation of ieee 802.15. 4k priority channel access with dsss phy," in *European Wireless 2015*. VDE, 2015, pp. 1–6.

[12] J. Markkula and J. Haapola, "Lte and hybrid sensor-lte network performances in smart grid demand response scenarios," in *Smart Grid Communications (SmartGridComm), 2013 IEEE International Conference on*. IEEE, 2013, pp. 187–192.

[13] F. Mwasilu, J. J. Justo, E.-K. Kim, T. D. Do, and J.-W. Jung, "Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration," *Renewable and Sustainable Energy Reviews*, vol. 34, pp. 501–516, 2014.

[14] T. Saaty, *The Analytic Hierarchy Process*. McGraw-Hill, 1980.

[15] J. A. Alonso and M. T. Lamata, "Consistency in the analytic hierarchy process: a new approach," *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, vol. 14, no. 04, pp. 445–459, 2006.

[16] J. Finan and W. Hurley, "Transitive calibration of the {AHP} verbal scale," *European Journal of Operational Research*, vol. 112, no. 2, pp. 367 – 372, 1999.

[17] Y. Dong, Y. Xu, H. Li, and M. Dai, "A comparative study of the numerical scales and the prioritization methods in ahp," *European Journal of Operational Research*, vol. 186, no. 1, pp. 229–242, 2008.

[18] Deliverable D3.3, "Device-to-device and hybrid sensor – telecom infrastructure specifications for smart energy grids," Peer to Peer Smart Energy Distribution Networks (P2P-SmarTest), Tech. Rep., 2016. [Online]. Available: http://www.p2psmartest-h2020.eu/deliverables

[19] J. Haapola, F. Martelli, and C. Pomalaza-Ráez, "Application-driven analytic toolbox for wsns," in *8th International Conference on Ad-Hoc Networks and Wireless (ADHOC-NOW)*, ser. LNCS 5793, September 2009, pp. pp. 112 – 125.

[20] J. Markkula and J. Haapola, "Ad hoc lte method for resilient smart grid communications," *Wireless Personal Communications*, Oct 2017. [Online]. Available: https://doi.org/10.1007/s11277-017-5018-1