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科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Distributed Control and Optimization for Networked Energy Resources with Limited Capacity Towards Autonomous Peer-to-Peer Microgrids

研究課題名（英文）Distributed Control and Optimization for Networked Energy Resources with Limited Capacity Towards Autonomous Peer-to-Peer Microgrids

研究代表者

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研究成果の概要（和文）：このプロジェクトでは、マイクログリッドのピアツーピアエネルギー市場のいくつかのモデルを提案しました。つまり、生産者と消費者の両方として機能するプロシューマーが他のプロシューマーと直接エネルギーを交換できる市場です。 このような市場では、プロシューマーは屋上ソーラー、燃料電池複合熱および電力ユニット、電気自動車、動的ワイヤレス充電を所有しています。サイバー攻撃に対する市場の堅牢性が調査され、既存の結果と比較してより優れたシステム回復力指数が得られました。

研究成果の学術的意義や社会的意義

- Academic significance: novel results on market structures, clearing mechanisms, and robustness for peer-to-peer energy markets.
- Social significance: better understanding toward realistic implementation of peer-to-peer energy markets.

研究成果の概要（英文）：This project was motivated by paradigm shifts in energy systems, where novel structures, operation principles and market mechanisms are required to achieve cleaner, more efficient, and more resilient energy systems. As such, this project proposed several models of peer-to-peer energy markets for microgrids, i.e. markets in which prosumers - who act as both producers and consumers - can directly trade energy with the others. In such markets, prosumers possess rooftop solar, fuel cell combined heat and power units, electric vehicles, dynamic wireless charging-discharging lanes, perovskite optical transceivers, etc. Hence, more renewable and distributed energy resources can be integrated into energy grids. Then market clearing mechanisms were analyzed using ADMM-based decentralized optimization methods, and distributed control methods were proposed. The market robustness to cyber-attacks were investigated, and a better system resilience index was obtained compared to the existing result.

研究分野：Applied math for energy

キーワード：P2P energy markets　smart grid　DERs　分散型最適化　distributed control　ADMM　wireless power transfer　resilience

１．研究開始当初の背景

Most parts of current electric power grids around the globe were built decades ago using the top-down approach, i.e. power is generated at central generation facilities located far away from end-users, which is then transmitted through very large transmission and distribution networks, incurring much power losses and costs for construction, maintenance, and expansion. In addition, conventional power plants based on fossil fuel resources are polluted causing severe problems to the environment and society, e.g. recent severe climate changes. Therefore, increase in deployment of renewable energy resources is a must to obtain clean power generation and reduce carbon emission. Moreover, the developed information and communication technologies have made the data collection and exchange between different grid components possible, leading to the concept of smart grid. Unfortunately, the large integration of renewable energy to the grid can cause crucial problems, e.g. frequency and voltage instability, because of the fluctuating and intermittent nature of renewable sources. Additionally, the central deployment of renewable generation, e.g., solar farms and wind farms, requires a large area, a high construction cost, and is not always accepted by the public. Thus, simply integrating renewable and distributed energy resources (DERs) into the current grids built based on a top-down approach is not an appealing solution.

Recently, there have been attracting directions on bottom-up approaches for building smart grids including the so-called peer-to-peer (P2P) energy systems. In small and local P2P energy systems, participants in local communities can directly communicate, share and trade energy, especially surplus renewable energy, without any central authority such as the aggregators. Hence, the issues of pollution, efficiency, flexibility, and autonomy of big and top-down conventional power grids can be avoided. This concept of P2P energy systems is different from the concept of microgrids – small scale power grids which usually still requires a central coordinating entity, but share one thing in common – the locality. Therefore, this project aims to investigate P2P microgrids to eliminate such difference toward autonomous microgrids.

However, in P2P microgrids (and other microgrids), the capacity of energy resources is limited due to their small-scale nature. Thus, the operation and control of such systems are different from that in large power grids, hence urging the need of novel control and optimization methods. From the control systems viewpoint, P2P microgrid is a network control system. Therefore, the limited energy capacity issue can be handled by designing proper control inputs, leveraging the framework of network system control and optimization. As such, the following key scientific questions were initially set to be solved in this project:

- ■ Key scientific question (Q1): Given a desired upper bound of the total control input energy for a network system, how to design a distributed controller satisfying that energy constraint?
- ■ Key scientific question (Q2): How to derive optimal energy management strategies for P2P microgrids in a fully distributed manner while taking into account P2P microgrid constraints including energy constraints?

２．研究の目的

The ultimate goal of this research proposal is to obtain theoretical designs for low carbon, energy-efficient, and autonomous smart microgrids which can operate on their owns, i.e. independent from the main grid, by which to improve the existing problems on the cleanliness, efficiency, flexibility, resiliency, and autonomy of electric power grids. To achieve that the key scientific questions (Q1) and (Q2) mentioned above were initially expected to be solved in this project.

Nevertheless, during the research period the principal investigator revised the research plan to mainly focus on the key scientific question (Q2), due to the following reasons. First, setting up a desired upper bound of total control input energy for the whole P2P microgrid incurs a global constraint. To deal with such global constraint in a distributed manner, additional efforts are needed, which also require additional energy consumption. Second, the upper bound in key scientific question (Q1) significantly limits the approaches for modeling, optimization and control of P2P microgrids. As such, the principal investigator mainly focused on resolving the key scientific question (Q2), in which energy constraints compose those for each P2P energy market participant and that for the energy balance constraint of the whole system.

３．研究の方法 (research method)

(1) Models of peer-to-peer (P2P) energy markets:

The first step in this research project is to specify mathematical models of P2P energy markets, based on which novel optimization and control methods will be developed. As such, during this research project a few P2P energy market models were investigated for integrating renewable and distributed energy resources, for instance, rooftop solar [J1], micro fuel cell combined heat and power (FC-CHP) systems [J2], electric vehicles and wireless charging-discharging lanes [J3], [J4], solar cells [J5], [J6]. Each market participant is a prosumer who can act as both an energy producer and an energy consumer.

The common point of P2P energy markets mentioned above is on the market structure which is described by a bipartite structure. More specifically, at each time step a P2P energy market is divided into two groups, one is for energy sellers and the other is for energy buyers, and the trading between participants (peers) are bilateral. For simplicity, no participant is both an energy seller and an energy buyer at the same time. Furthermore, there is no communication between participants inside each group. Instead, the communications are made between a participant in one group with some others in the remaining group, and this structure can be changed from a time step to another. This time-varying bipartite structure is illustrated in Figure 1 below.

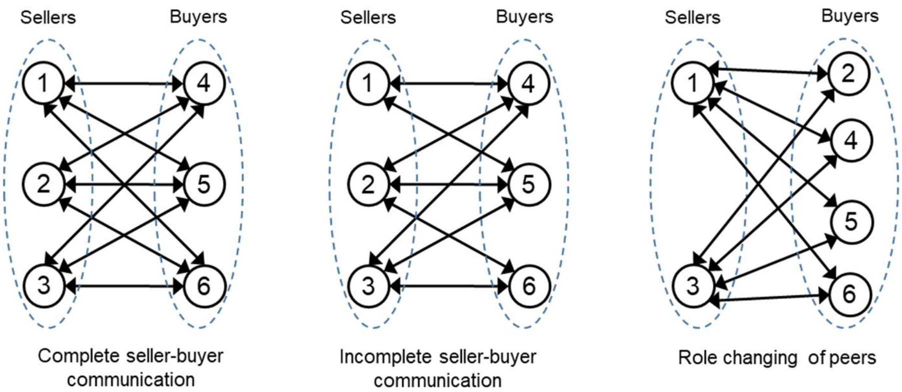

Figure 1. Illustration of the time-varying bipartite structure in the considered P2P energy markets (6 participants are used for illustration purpose only) [J1].

(2) P2P market clearing mechanisms:

Having the specific models of P2P energy markets as described above, this research project proposed market clearing mechanisms and studied related problems. The market clearing problem is formulated as a decentralized optimization problem to be solved by each market participant (peer). To do so, the so-called alternating direction method of multipliers (ADMM) approach is employed to develop decentralized approaches to solve the aforementioned decentralized optimization problems, i.e. to solve market clearing problems.

４．研究成果 (research result)

During the period of this research project, many results have been obtained, some of which were not thought of in the original research plan. For example, the bidirectional optical wireless power transfer between perovskite solar cell devices [J5], [J6] can be treated under the framework of P2P energy systems, in which in system containing a perovskite solar cell device can be regarded as a peer. In what follows, the main research results on P2P energy markets derived from this research project are described.

A comparison between P2P energy markets and conventional pool-based energy markets was made in [J1], together with an analysis of P2P energy market closed-form solutions with and without bilateral trade weights. Then an ADMM-based market clearing mechanism was proposed in [J1] for the general case of having bilateral trade weights. Based on the obtained results, simple learning strategies were proposed to adjust prosumer cost function parameters to achieve successful and maximum traded powers for all prosumers. All theoretical results were subsequently demonstrated via a synthetic system and a modified IEEE European Low Voltage Test Feeder.

Utilizing the research in [J1] as a base, the study in [J2] investigated a P2P energy market for residential prosumers equipped with micro FC-CHP units, in which the simultaneous gas and electricity management was considered. Then by linearizing the nonlinear dynamics of FC units, the original non-convex, nonlinear optimization problem representing the optimal gas-electricity management was convexified and solved using the ADMM approach proposed in [J1] for the considering P2P electricity market. It is then illustrated through an example of 6-house system with realistic electricity consumption that the considered P2P electricity trading system help households to be as self-sufficient as possible, and the electricity bought from the bulk grid is as least as possible, as depicted in Figure 2. It is also noted that the ADMM approach in [J1] and [J2] are scalable.

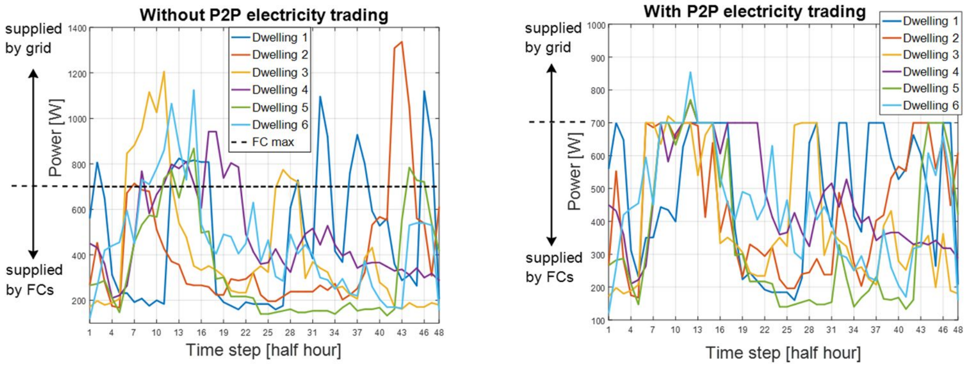

Figure 2. Demonstration for the effectiveness of a P2P electricity trading market [J2].

Next, a P2P energy market was proposed in [J3] for the energy trading between electric vehicles (EVs) and road lanes embedded with coils for bidirectional wireless charging and discharging with EVs. Moreover, the negotiation for energy trading between EVs and a wireless charging-discharging lane (WCDL) is masked with random noises so that their privacy is protected, while still achieving the averaged consensus for calculating the market-clearing energy price. Consequently, a cooperative learning based on interval analysis was proposed in [J3] for selecting parameters of the cost functions of EVs and a WCDL so that their traded amounts and the market-clearing price belong to their desired intervals.

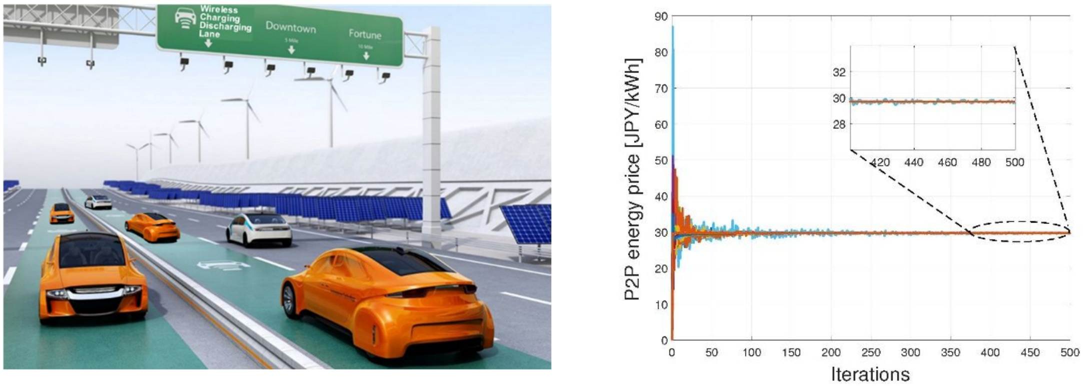

Figure 3. Illustration for the P2P energy trading between EVs and a WCDL and the masked market-clearing price [J3].

Lastly, following the work initiated in [J3], the study in [J4] generalized it to the general case of multiple energy buyers and multiple energy sellers. The problem of determining the ranges for prosumer cost function parameters so that the resulted P2P energy market-clearing solutions belong to expected intervals by prosumers was formulated as an inverse optimization problem. A cooperative learning strategy was then proposed for all prosumers to collaborate with other prosumers in via the specified bipartite communication structure to satisfy a global inequality condition. Afterward, the robustness of the considered P2P energy market was investigated in presence of various models of cyberattacks including Byzantine, malicious, F-local, and f-fraction types of cyberattacks. It was shown that under the so-called weighted-mean-subsequence-reduced (WMSR) resilient consensus algorithm (for inter-prosumer negotiation), the inter-prosumer bipartite communication structure possesses a much better resilience performance index than that in the existing literature. This can be seen via a numerical example shown in Figure 4 below.

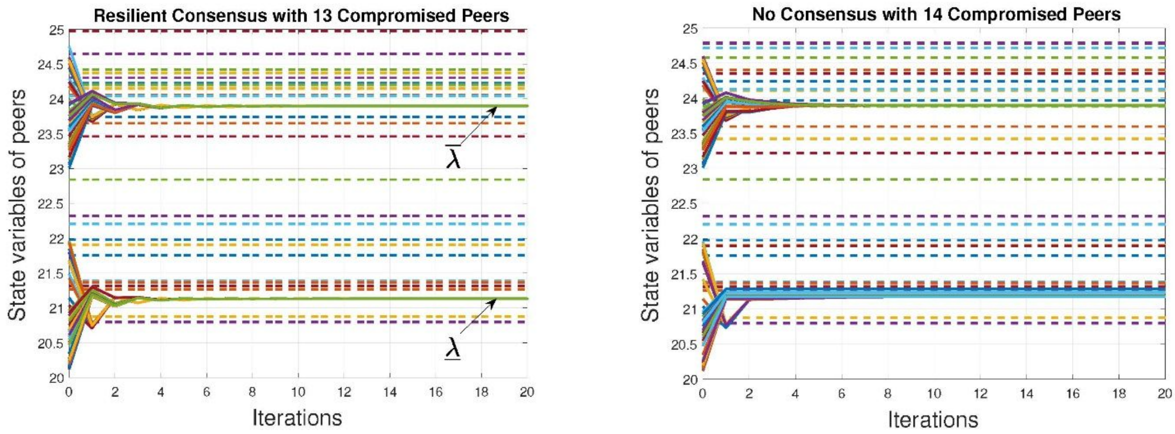

Figure 4. Demonstration for the tightness of the resilience performance index of bipartite P2P energy markets obtained in [J4].

Main publications

[J1] Dinh Hoa Nguyen, "Optimal Solution Analysis and Decentralized Mechanisms for Peer-to-Peer Energy Markets", IEEE Transactions on Power Systems, vol. 36(2), pp. 1470-1481, 3/2021. DOI: 10.1109/TPWRS.2020.3021474

[J2] Dinh Hoa Nguyen, Tatsumi Ishihara, "Distributed Peer-to-Peer Energy Trading for Residential Fuel Cell Combined Heat and Power Systems", International Journal of Electrical Power and Energy Systems, vol. 125, February 2021, 106533. DOI: 10.1016/j.ijepes.2020.106533

[J3] Dinh Hoa Nguyen, "Electric Vehicle – Wireless Charging-Discharging Lane Decentralized Peer-to-Peer Energy Trading", IEEE Access, vol. 8, pp. 179616-179625, 2020. DOI: 10.1109/ACCESS.2020.3027832

[J4] Dinh Hoa Nguyen, "A Cooperative Learning Approach for Decentralized Peer-to-Peer Energy Trading Markets And Its Structural Robustness Against Cyberattacks", IEEE Access, vol. 9, pp. 148862-148872, 2021. DOI: 10.1109/ACCESS.2021.3125031

[J5] Dinh Hoa Nguyen, Ganbaatar Tumen-Ulzii, Toshinori Matsushima, Chihaya Adachi, "Performance Analysis of A Perovskite-based Thing-to-thing Optical Wireless Power Transfer System", IEEE Photonics Journal, vol. 14(1), 6213208, 2022. DOI: 10.1109/JPHOT.2022.3146365

[J6] Dinh Hoa Nguyen, Toshinori Matsushima, Chuanjiang Qin, Chihaya Adachi, "Towards Thing-to-Thing Optical Wireless Power Transfer: Metal Halide Perovskite Transceiver As An Enabler", Frontiers in Energy Research, vol. 9, 679125, 2021. DOI: 10.3389/fenrg.2021.679125

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１．著者名 Daniel Packwood, Linh Thi Hoai Nguyen, Pierluigi Cesana, Guoxi Zhang, Aleksandar Staykov, Yasuhide Fukumoto, Dinh Hoa Nguyen	４．巻 8(15)
２．論文標題 Machine Learning in Materials Chemistry: An Invitation	５．発行年 2022年
３．雑誌名 Machine Learning with Applications	６．最初と最後の頁 100265
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.mlwa.2022.100265	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Dinh Hoa Nguyen, Ganbaatar Tumen-Ulzii, Toshinori Matsushima, Chihaya Adachi	４．巻 14(1)
２．論文標題 Performance Analysis of A Perovskite-based Thing-to-thing Optical Wireless Power Transfer System	５．発行年 2022年
３．雑誌名 IEEE Photonics Journal	６．最初と最後の頁 6213208
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/JPHOT.2022.3146365	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Dinh Hoa Nguyen	４．巻 9
２．論文標題 A Cooperative Learning Approach for Decentralized Peer-to-Peer Energy Trading Markets And Its Structural Robustness Against Cyberattacks	５．発行年 2021年
３．雑誌名 IEEE Access	６．最初と最後の頁 148862-148872
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ACCESS.2021.3125031	査読の有無 有
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１．著者名 Dinh Hoa Nguyen, Andrew Chapman	４．巻 14(6)
２．論文標題 The Potential Contributions of Universal and Ubiquitous Wireless Power Transfer Systems Toward Sustainability	５．発行年 2021年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1080/19397038.2021.1988187	査読の有無 有
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1．著者名 Dinh Hoa Nguyen	4．巻 13(15)
2．論文標題 Residential Energy Consumer Occupancy Prediction based on Support Vector Machine	5．発行年 2021年
3．雑誌名 Sustainability	6．最初と最後の頁 8321
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/su13158321	査読の有無 有
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1．著者名 Dinh Hoa Nguyen, Javad Khazaei	4．巻 12(4)
2．論文標題 Unified Distributed Control of Battery Storage with Various Primary Control in Power Systems	5．発行年 2021年
3．雑誌名 IEEE Transactions on Sustainable Energy	6．最初と最後の頁 2332-2341
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TSTE.2021.3091976	査読の有無 有
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1．著者名 Dinh Hoa Nguyen, Toshinori Matsushima, Chuanjiang Qin, Chihaya Adachi	4．巻 9
2．論文標題 Towards Thing-to-Thing Optical Wireless Power Transfer: Metal Halide Perovskite Transceiver As An Enabler	5．発行年 2021年
3．雑誌名 Frontiers in Energy Research	6．最初と最後の頁 679125
掲載論文のDOI（デジタルオブジェクト識別子） 10.3389/fenrg.2021.679125	査読の有無 有
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1．著者名 Dinh Hoa Nguyen, Tatsumi Ishihara	4．巻 125
2．論文標題 Distributed Peer-to-Peer Energy Trading for Residential Fuel Cell Combined Heat and Power Systems	5．発行年 2021年
3．雑誌名 International Journal of Electrical Power and Energy Systems	6．最初と最後の頁 1-9
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1．著者名	4．巻
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2．論文標題	5．発行年
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3．雑誌名	6．最初と最後の頁
IEEE Transactions on Power Systems	1470-1481
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1109/TPWRS.2020.3021474	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	該当する

1．著者名	4．巻
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2．論文標題	5．発行年
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10.1109/ACCESS.2020.3027832	有
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2．論文標題	5．発行年
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10.1049/iet-est.2020.0014	有
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1．著者名 Thiem Van Pham, Nadhir Messai, Dinh Hoa Nguyen, Noureddine Manamanni	4．巻 140
2．論文標題 Robust Formation Control Under State Constraints of Multi-Agent Systems in Clustered Networks	5．発行年 2020年
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1．著者名 Javad Khazaei, Dinh Hoa Nguyen, Arash Asrari	4．巻 PP
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4．発表年
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2．発表標題
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１．発表者名
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２．発表標題
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３．学会等名
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４．発表年
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１．発表者名
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１．発表者名
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2019年

〔図書〕　計5件

１．著者名 Javad Khazaei, Dinh Hoa Nguyen, Arash Asrari	４．発行年 2021年
２．出版社 The Institution of Engineering and Technology (IET)	５．総ページ数 381
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２．出版社 IntechOpen	５．総ページ数 170
３．書名 Research Trends and Challenges in Smart Grids	

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関