（ 続紙 1 ）

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論文題目	Investigating the mechanism of interactions between carbon pricing policy and capacity mechanism (炭素価格付け政策と容量メカニズムの相互作用の探究)		

（論文内容の要旨）

This study explores the interaction between carbon pricing policy and capacity mechanism in liberalized electricity markets. The thesis is comprised of five chapters, each focusing on a specific aspect of the study.

Chapter 1 provides an overview of the research, including the research background, aims, and significance. The existing literature related to the research problem is reviewed from five aspects: carbon pricing policy, capacity mechanism, interaction among mixed policies, and simulation-based policy design methods.

Chapter 2 proposes a conceptual framework for studying policy interactions, aimed at exploring the interactions between carbon pricing policy and capacity mechanism in liberalized electricity markets. Using the traditional System Dynamics model to simulate the trajectory changes of power mix in order to verify the framework. The results show that the proposed framework can be used for supporting quantitative analyze the interaction between policies. It is found that there are potential conflicts between carbon pricing policy and capacity mechanism in liberalized electricity markets.

Chapter 3 describes the development of an optimization-embedded hybrid System Dynamics model. This is aimed at reducing the simulation bias of the traditional System Dynamics method in the high variable renewable energy (VRE) penetration system, since the traditional method is difficult to model the technical details of grid dispatching. By comparing the changes in power capacity installation changes, electricity generation, carbon emissions, and other indicators under different policy implementation scenarios, it is found that the traditional model overestimates the emission reduction effect of carbon pricing policy and the stability of the system. The bias of the traditional method increases with the introduction of VRE. Thus, confirming the rationality and effectiveness of the hybrid System Dynamics model in studying the interaction between carbon pricing policy and capacity mechanism.

Chapter 4 follows the proposed framework to simulate the power mix trajectory changes using the hybrid model, thereby investigating the interactions between the two policies and their effects. Results demonstrate that the interaction between carbon pricing

policy and capacity mechanism is contingent on the specific policy design and intensity, with conflicts or synergies varying across different perspectives. If policymakers prioritize emission reduction, a high carbon floor price with flexible resources focus capacity mechanism show synergies, especially under high VRE deployment. Conversely, if economic benefits are the primary goal, policymakers may consider a basic carbon floor price with a thermal power-focused capacity mechanism, regardless of VRE deployment.

Chapter 5 summarizes the main conclusions and explains future work.

The contributions of the study are primarily:

- a quantitative analysis framework for policy interaction mechanisms, thereby allowing to study of the relationship between carbon pricing policies and capacity mechanism in liberalized electricity markets.
- an optimization-embedded hybrid System Dynamic model, improved the simulation abilities of System Dynamics by adding technical details of grid dispatch.
- Clarification of the interaction between carbon pricing policy and capacity mechanism in liberalized electricity market, providing references for understanding the trade-off in policy design of energy system transition.

Overall, this study provides valuable insights into the interaction between carbon pricing policy and capacity mechanism in liberalized electricity markets. The findings of this study can help policymakers make comprehensive decisions on energy policies and provide a foundation for future research in this field.

（続紙 2 ）

（論文審査の結果の要旨）

Liberalized electricity markets have emerged across the world, including in Japan in recent years, with hopes that they will provide competition and efficiently reduce prices for consumers. When conventional fossil fuels are used, the demand-supply balance can be readily assured, but CO_2 is emitted, exacerbating global warming. Policies such as carbon taxes and feed-in-tariffs are applied to such markets to reduce CO_2 emissions and introduce renewable energy. But variable renewable energy (VRE) such as solar photovoltaics and wind power cannot be controlled, leading to problems with demand-supply balance. Additionally, if the carbon price is too high, then fossil-fuel generators will rapidly leave the market, leaving a gap in supply. To address the latter issue, capacity prices are applied to maintain sufficient supply capacity. When more than one of these policies is implemented, they may have complex interactions, potentially leading to reduced effectiveness – for example, fossil fuel power stations could be paid a capacity price but required to pay a carbon price. Thus there is a need to develop quantitative models that can be used to test the outcomes on the energy system when multiple policies are applied at the same time.

This thesis developed three models of increasing complexity to address these problems, using system dynamics and optimization techniques, and applied the models to the case study of Hokkaido, Japan. The following three contributions to knowledge were obtained:

1. A framework for quantitative analysis of the interaction between carbon policy and capacity mechanism was developed.
2. A hybrid method that embedded optimization into system dynamics model and allows the consideration of detailed technical factors with different time scales in policy simulation was developed and showed that typical models lead to overly-optimistic results, which can be mitigated with this model.
3. The specific effects on power mix trajectories were identified, considering the interaction between the two policies under 11 different scenarios, showing that under high VRE scenarios the conflicts become larger, and traditional models do not sufficiently show the difference. The implementation of high carbon prices and high feed-in-premiums along with capacity prices targeting flexible power plants (LNG) produces synergies leading to lower emissions, but the integration of VRE reaches a limit and

cannot provide zero emissions unless further measures are taken. When there is no discrimination between fossil fuel capacity, and when the carbon price is lowered, the policies show conflicts, leading to lower efficiency and higher emissions.

よって、本論文は博士（エネルギー科学）の学位論文として価値あるものと認める。また、令和５年７月２８日実施した論文内容とそれに関連した試問の結果合格と認めた。

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