Taikichiro Mori Memorial Research Grants 2021

Research Achievement Report

Project title: Household Food-energy-water nexus simulation: An integrated resource system with distributed energy

Name: Liu Hanyu Keio University, Graduate school of Media and governance

Introduction

The household sector accounts for a large proportion of the total resource consumption and carbon emissions. In 2019, the global residential building sector contributed to 22% energy use and 17% carbon emissions(Programme & Construction, 2020). Therefore, attention to the management of household natural resource consumption is of great significance to resource conversation and decarbonization.

With the increasingly widespread use of renewable energy, the introduction of distributed energy source gives more potential for household decarbonization. Distributed energy generation not only allows households to reduce their carbon emissions through clean energy, but also increases resilience by reducing the household sector's reliance on centralized energy supplies. Also, households can generate benefits from the sale of excess electricity. In addition, rainwater harvesting and grey water recycling systems are useful for saving water, especially for households with gardens or vegetable cultivations, which can be irrigated with the collected rainwater.

The potential for the introduction of new technologies varies between different types of domestic dwellings, and there are many alternative system types available depending on demand, for example, wind, solar and hydrogen systems, while solar energy has different types of application, which includes PV, solar thermal systems, etc.(Lamnatou et al., 2015). However, the high initial installation and maintenance costs, the lack of space for the equipment installation, and the vulnerability of the performance of distributed energy sources to weather conditions are all the problems that can be encountered with household distributed energy use.

Also, the resource requirements of each household vary depending on the type of the building, the size of the household, the specifications of the appliance and the lifestyle. The Japanese Agency for Natural Resources and Energy (JANREA) has compiled information on energy-efficient products and produced a standardized energy saving label for households that are shopping for appliances to help them reduce their energy consumption and financial expenditure. Furthermore, the development of a lifestyle that seeks convenience and comfort has led to a significant increase in energy consumption in the household sector. However, since the Great East Japan Earthquake, there has been a downward trend in household energy consumption due to increased awareness of energy saving measures such as electricity conservation and laws enacted to improve the energy performance of buildings.

On the other hand, food, energy and water, as the main consumption resources in the household sector, are closely linked in the daily life scenarios. For example, the cooking of general food consumes energy and water, while energy is used to heat water. The concept of the Food-Energy-Water Nexus (FEW Nexus) was developed to describe the interactions between these three resources(Zimmerman et al., 2018), such as trade-off and synergies, and to link the Food-Energy-Water Nexus with sustainability and resilience. The FEW Nexus reminds us of the need to manage household resource in a holistic manner and to analyze the implications of changes in resource flows for resource conservation and decarbonization.

Based on the FEW Nexus concept, most studies have examined the interrelationships between energy, food and water at the city and national levels, while in recent years some attention has been paid to the analysis of the FEW Nexus at the household level. In contrast, the analysis of FEW Nexus at the household level has received more attention in recent years. Hussien developed an integrated model of system dynamics that captures the interactions between WEF at the end-use level at the household scale, and through which the demand for household FEW and the generation of organic waste and wastewater (Hussien et al., 2017). Subsequently, the model was further used to assess the probability of risk of a per capita FEW demand shortfall in the household sector exceeding an acceptable range, taking into account seasonal variations and uncertainties in the supply-demand balance. And to assess the impact of local resource management policies on household FEW Nexus, using the example of Duhok, with a view to finding the most effective strategies that could lead to a sustainable supply of water, energy and food (Hussien et al., 2018). Since then, several studies have further analyzed the impact of behavior, equipment efficiency and resource prices on household FEW consumption, modelled the behavioral choices of household resource use and assessed the effects of various policies on reducing household consumption through scenario analysis. However, as these studies assess regional household sector average annual FEW consumption, they do not consider the effects of household size differences and seasonal variations (Casazza et al., 2021; Xue et al., 2021) (Januar, 2018). In addition, Foden uses the example of FEW Nexus to address the problem of sewer blockages caused by fat, oil and grease in the kitchen to illustrate the significance of understanding 'household nexus' and reconstructing household sustainability interventions based on FEW Nexus (Foden et al., 2019). Jennifer proposes a new framework based on disaster risk theory and Food-Energy-Water (FEW) Nexus systems thinking to analyze the collective impact of integrated infrastructure disruptions and socio-economic factors on household vulnerability during disasters (Dargin et al., 2020).

In terms of the analysis of interactions between households' FEW, Hussien considered water-related energy use, food-related energy and water use, energy-related water use, wastewater and since then, studies have included the use of more household devices and the interactions between FEW at the household level arising from the resource consumption of these devices, while assessing the direct and indirect CO_2 emissions arising from household consumption based on life cycle analysis. Some studies have analyzed the impact of technological tools on household resource consumption, such as household water recycling and the use of anaerobic digestion for energy recovery from kitchen waste and wastewater sludge (Hussien et al., 2018). However, no study has uniformly analyzed the impact of applying these technological tools. In particular, as new energy devices such as distributed energy sources are being introduced and used in the household sector, there are many uncertainties associated with distributed energy sources themselves, i.e., stability, economic costs, etc. (Lamnatou et al., 2015), so it is essential to systematically consider the impact of distributed energy sources, including solar power, on household resource consumption. On the other hand, carbon emission reduction has become a focus of attention, and as the assessment of household consumption and carbon emissions has previously been limited to the indoor context (Xue et al., 2021), it is possible to consider both outdoor household consumption and the resulting carbon emissions (e.g., transport) to help optimise the management of resources in the household sector and promote carbon reduction. Therefore, this research considered to integrate series of advanced technologies and practices, including distributed energy, family garden and Greywater recycling, rainfall harvesting system into the Household FEW Nexus simulation, examine the effects of each technology or practice on household FEW consumption and interactions of nexus. Also, family size, seasonal and weather variations are taken as variables to simulate the operation of household FEW Nexus under different scenarios of the applications of technologies and practices. Finally, household FEW Nexus is evaluated from the perspectives of resource consumption, CO2 emission. Based on the research, we could understand the interactions of FEW Nexus and simulate the policy effect, so as to provide some hints for policy makers.

Method

Due to the complexity of household FEW nexus, system dynamics is used to simulate and analyze the dynamic variations of interactions between FEW and its influences. System dynamics is a science which studies the structure and behavior of system feedback by combining system science theory and computer simulation closely, which has been used extensively to simulate environmental and climate problems at various scales(Mereu et al., 2016; Qi & Chang, 2011).
Figure 1 shows the structure of the developed household food-energy-water nexus (FEW Nexus) and uses it as a basis for modelling the system dynamics of the household FEW Nexus. The consumption of water, energy and food will be based on the resource usage of each end device within the home. Also, the model considered the application of advanced technologies and practices. Water harvesting, water recycling and water storage have been considered in the aspects of water, while distributed energy equipment including PV panel, cell-fuel, electrolytic, methanation plant and storage tank have been included into the model. The key variables of household FEW Nexus model are the impact of family size, season and weather variations on household FEW consumption and the performance of distributed energy generation. In addition to track of household FEW use, the interactions between food, water and energy and carbon emissions are simulated as well.

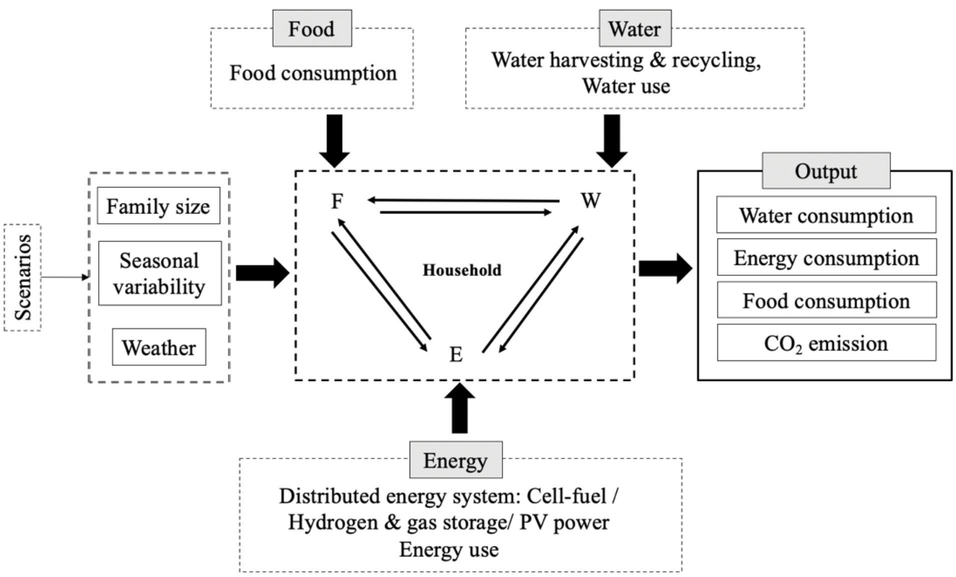

Fig. 1. The structure of the water-energy-food nexus at a household scale

Fig.2 shows a schematic diagram of a household food-energy-water nexus system that integrates the application of various advanced technologies and practices. The integrated system consists of photovoltaic power generation, a fuel cell (Ene-farm), an electrolytic cell hydrogen production plant, a hydrogen methanation plant, a hydrogenation station, a natural gas storage tank and grey water recycling.

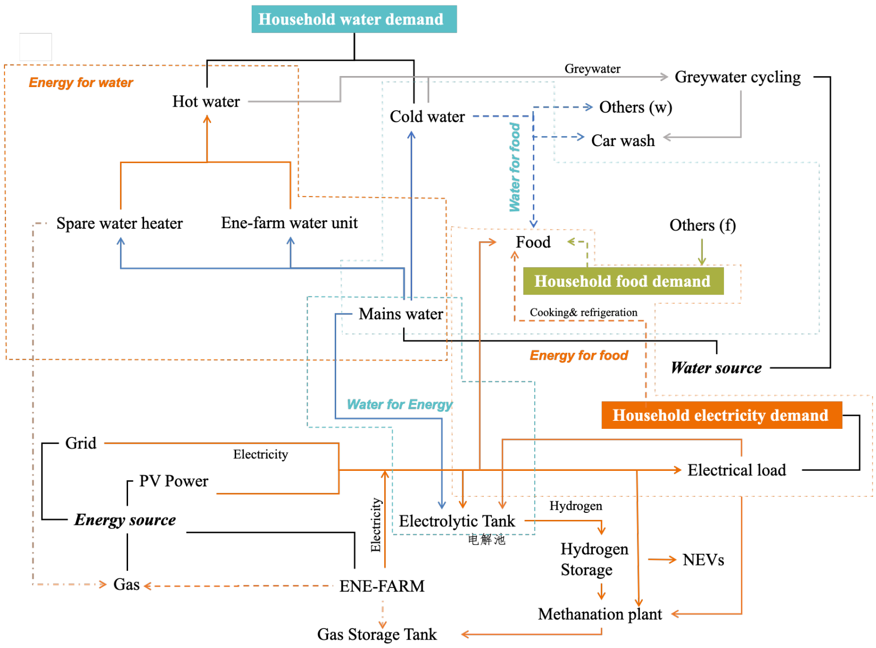

Fig.2. Schematic diagram of household food-energy-water nexus system

In the energy sub-system, the electrical load is provided by photovoltaic power and fuel cells as well as the external grid. The excess light energy output is fed to the electrolytic cell unit to produce hydrogen and stored in a hydrogen storage tank, which functions primarily for the fuel cell vehicle. When the storage tank reaches its maximum storage state, a methanation unit is activated to convert the hydrogen into methane for input into the system natural gas network. The heat generated by the fuel cell (Ene-Farm) can be used for hot water heating, while the natural gas storage tank acts as a back-up supply source and its stored natural gas can support the fuel cell operation. In the water sub-system, grey water is recycled for car washing. In order to analyze the impact of advanced technologies and practices on the household FEW Nexus, we combined different technologies and practices as different scenarios.

Based on the fig.2, interactions of household food-energy-water nexus and carbon emissions shown in fig.3 can be figured out. There are 4 types of variables shown in the Fig.3, including food-related, water-related, energy-related and emission-related variables. The direction of an arrow shows the interactions between the variables of FEW Nexus. For example, food consumption triggers the energy and water use, water-using appliances trigger the energy consumption for water and water use for energy.

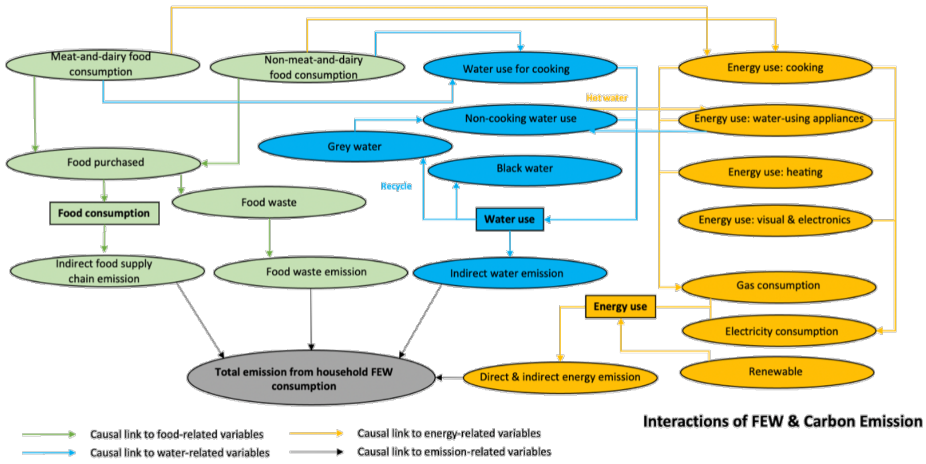

Fig.3. Interactions of household food-energy-water nexus and carbon emissions

Research Progress

During the past year, the framework and research methodology of the study were refined based on a clear research question. The study has developed a modelling framework for the Family FEW Nexus and has based the model on the framework. At the same time, data has been actively acquired and a database of household devices has been created. In addition, data on the energy systems of buildings and individual houses have been obtained and will be further applied and analyzed. So far, preliminary simulation results for the household FEW Nexus have been analyzed for this study.

*As this research project involves unpublished data, we will not be able to publish detailed results or data. We thank you in advance for your understanding.

Acknowledgments

Taikichiro Mori Memorial Research Grants has paid for the purchase of computers and external hard drives for data analysis, enabling me to analyze the data more effectively. I would like to thank the support from Taikichiro Mori Memorial Research Grants.