A Transactive Energy Approach to the Water-Energy-Food Nexus

Andrea Cusva-García[1], Rodrigo Palma-Behnke[2], Nicanor Quijano[1], Guillermo Jiménez-Estévez[1], and Patricio Mendoza-Araya[2]
[1]Dept. de Ingeniería Eléctrica y Electrónica, Universidad de los Andes, Bogotá, Colombia
[2]Centro de Energía, Dept. Ingeniería Eléctrica, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Santiago, Chile
Emails: ac.cusva10@uniandes.edu.co, rodpalma@cec.uchile.cl, nquijano@uniandes.edu.co, ga.jimeneze@uniandes.edu.co, pmendoza@centroenergia.cl

***Abstract*—This paper introduces the *WEF Token*, a transactive coordination mechanism that internalizes the physical and economic interdependencies among water, energy, and food (WEF) resources. Derived endogenously from a welfare–maximizing optimization model, its value corresponds to the shadow price of the energy balance, providing a unified unit of account that links resource flows, opportunity costs, and social welfare. The proposed framework integrates a hybrid PV–diesel system, water pumping, and agricultural production, and incorporates the distinct roles involved in operating and using these resources, thereby bridging centralized welfare optimization with decentralized decision-making. Sensitivity and multi-scenario analyses demonstrate that the *WEF Token* behaves as a scarcity-sensitive price signal, enabling consistent multi-resource coordination and providing actionable insights for planning within community-scale agro-energy systems.**

***Index Terms*—Transactive energy; Water-energy-food nexus, energy management and transactions.**

I. Introduction

The Transactive Energy (TE) framework enables the economic optimization of distributed resources through local market interactions and dynamic price signals [1]. While TE has been extensively studied in electricity systems and, more recently, in multi-energy settings [2], [3], its application to systems physically coupled with water and food resources remains unexplored. The Water–Energy–Food (WEF) Nexus framework explicitly captures the interdependencies among these resources [4]. However, most WEF optimization models rely on exogenously defined prices or aggregated monetary objectives [5], and therefore do not generate endogenous coordination signals. Although multi-objective WEF formulations characterize trade-offs among water, energy, and food resources, they lack mechanisms for decentralized coordination [6]. Building upon these gaps, this paper introduces the *WEF Token*, a local accounting unit that represents the joint energetic and scarcity value WEF resources. Inspired by the principles of community and local currencies, which aim to retain value within a defined territory [7], promote local economic resilience [8], and strengthen resource circularity [9], [10], the WEF Token bridges physical and economic domains by translating welfare-based dual variables into operational price signals. Unlike conventional monetary systems that externalize ecological costs, or blockchain-based schemes such as NRGcoin [11], which reward renewable electricity generation without an explicit welfare formulation, the WEF Token emerges endogenously from the welfare optimization of a physically coupled WEF system. It is not conceived as a speculative cryptocurrency or blockchain-based asset, but rather as a transactive signal derived from the shadow value of energy, internalizing the opportunity costs of interdependent resources and providing a consistent valuation basis for multi-resource exchanges. To the best of the authors' knowledge, no prior study has reported a token endogenously derived from a physically coupled WEF optimization framework.

The proposed WEF–transactive mechanism integrates multiple households, a hybrid PV–diesel energy subsystem, a water pumping unit, and an agricultural production process within a single optimization structure. By interpreting the dual variables of the Karush–Kuhn–Tucker (KKT) conditions as operational price signals, the framework bridges centralized welfare optimization and decentralized transactive operation, establishing a unified mechanism that links physical resource flows, economic efficiency, and local market coordination. Accordingly, the contributions of this paper are twofold. First, it formulates a physically coupled community-scale WEF model and demonstrates that the endogenous shadow prices of energy and water constraints induce a transactive mechanism in which a single *WEF Token* consistently prices electricity, pumped water, and food through opportunity costs. Second, it presents sensitivity and multi-scenario analyses showing that these prices internalize resource scarcity and effectively bridge welfare optimization with decentralized coordination, providing actionable insights for the planning of sustainable agro-energy systems at the community level.

II. Problem Statement

This section outlines the community-scale WEF optimization model and its transactive formulation, grounded in microeconomic theory [12]. The framework couples physical resource interactions with welfare-maximizing coordination principles to derive equilibrium-based transactive price signals.

This work was supported on part by the project BPIN 2021000100499, funded by CTel–SGR and Minciencias, Colombia, and by the *Beca Impacto País*.

979-8-3315-8138-1

A. System Description and Agents

The community system comprises four interacting agents:

- Households ($i \in \mathcal{H}$): residential consumers of electricity $E_{H,i}$ [kWh/day] and water $W_{H,i}$ [m^3/day], deriving utility $U_{H,i}$.
- Agricultural producer (A): crop production unit requiring energy E_A [kWh/day] and water W_A [m^3/day] to generate food output Y [kg/day].
- Distributed system operator (DSO) (E): coordinates local energy generation from photovoltaic (E_{PV}) and diesel (E_{DG}) generators, ensuring supply-demand balance.
- Water utility (W): manages water extraction and pumping, providing usable water $W_\text{u} = \eta_W W_\text{s}$ with efficiency η_W.

A Community Coordinator (CC) acts as a social planner that maximizes the aggregated community welfare subject to physical and resource constraints.

B. Economic and Physical Models

Each household derives logarithmic utility from daily energy and water consumption, expressed as

$$U_{H,i}(E_{H,i}, W_{H,i}) = \alpha_i \ln\left(\frac{E_{H,i}}{\hat{E}_{H,i}}\right) + \beta_i \ln\left(\frac{W_{H,i}}{\hat{W}_{H,i}}\right), \quad (1)$$

where $(\hat{E}H, i, \hat{W}H, i)$ represent the reference (target) consumptions for electricity and water. The parameters α_i and β_i denote the relative preference weights of household i, both non-negative and calibrated from the reference social energy price p_0 [USD/kWh]. Since both energy and water demands are monetized through their energy-equivalent valuation, these parameters are defined as $\alpha_i = p_0 \hat{E}_{H,i}$ and $\beta_i = p_0 \gamma_W \hat{W}_{H,i}$, where γ_W [kWh/m^3] converts water use into its energy-equivalent representation. As a result, $U_{H,i}$ is expressed in [USD/day], ensuring dimensional consistency with the economic terms of the objective function. The logarithmic functional form is grounded in standard microeconomic and welfare theory, where it is commonly used to represent fairness in the allocation of essential resources [12].

Moreover, agricultural production is modeled through a Cobb–Douglas function of water and energy inputs, whose economic value is expressed as $U_A = p_Y Y$. The Cobb–Douglas formulation is adopted as a reduced-form and widely used representation in agricultural studies [13]. Hence,

$$Y = A_0, W_A^\theta E_A^\phi, \qquad \theta > 0, \phi > 0, \theta + \phi < 1, \quad (2)$$

where p_Y [USD/kg] denotes the local price of agricultural output, and the parameters θ and ϕ represent the elasticities of production with respect to water and energy, while A_0 is the total factor productivity coefficient that captures the overall efficiency of the agricultural system. Furthermore, water and energy are physically coupled through the pumping subsystem, where the total energy required for water extraction from the source is denoted as $E_\text{PS} = \gamma_W W_\text{s}$, and the effective usable water delivered to end users is $W_\text{u} = \eta_W W_\text{s}$. Here, W_s represents the raw water extracted from the source, W_u the usable water available for consumption, η_W the overall hydraulic efficiency of the system, and γ_W the specific pumping energy, derived from hydraulic principles, as $\gamma_W = \frac{\rho g H}{\eta_\text{PS} 3.6\times10^6}$, where ρ is water density, g the gravitational acceleration, H the total dynamic head, and η_PS the combined pump–motor efficiency. Besides, the DSO allocates energy among community users and the pumping system while ensuring supply-demand balance. PV output is limited by its daily production capacity, satisfying $0 \leq E_{PV} \leq \overline{E}_{PV}$, while diesel generation is modeled as a convex cost function subject to $E_{DG} \geq 0$:

$$C_{DG}(E_{DG}) = a_{DG} E_{DG} + b_{DG} E_{DG}^2, \quad (3)$$

where C_{DG} represents the daily operating cost and a_{DG}, b_{DG} are the linear and quadratic cost coefficients.

C. Centralized Welfare Optimization

The CC determines the optimal allocation of energy and water resources by maximizing the total community welfare, which aggregates the residential and agricultural utilities (Eq. (1)–Eq.(2)) while subtracting the generation costs (Eq. (3)). The decision vector is defined as $\mathbf{x} = \{E_{H,i}, W_{H,i}, E_A, W_A, E_{PV}, E_{DG}, W_\text{s}\}$, encompassing all resource flows within the system. The welfare maximization problem is formulated as

$$\begin{aligned} \max_{\mathbf{x}\geq 0}\ \mathcal{W}(\mathbf{x}) = \sum_{i\in\mathcal{H}} \Big[\alpha_i \ln\left(\frac{E_{H,i}}{\hat{E}_{H,i}}\right) + \beta_i \ln\left(\frac{W_{H,i}}{\hat{W}_{H,i}}\right)\Big] \\ + p_Y A_0 W_A^\theta E_A^\phi - (a_{DG} E_{DG} + b_{DG} E_{DG}^2), \end{aligned} \quad (4)$$

where $\mathcal{W}$ is in [USD/day], ensuring dimensional consistency across all model components. All parameters use conventional monetary units to preserve interpretability and enable calibration with real techno-economic data. To address the physical interdependence between energy and water flows, the optimization incorporates the following constraints:

$$\sum_{i\in\mathcal{H}} E_{H,i} + E_A + \gamma_W W_\text{s} = E_{PV} + E_{DG}, \quad (5)$$

$$\sum_{i\in\mathcal{H}} W_{H,i} + W_A = \eta_W W_\text{s}, \quad (6)$$

$$\sum_{i\in\mathcal{H}} W_{H,i} + W_A \leq \overline{W}. \quad (7)$$

Eq. (5) enforces the energy balance between total demand and hybrid generation, while Eq. (6) establishes the coupling between extracted and usable water. Finally, constraint Eq. (7) introduces the environmental water cap $\overline{W}$. The corresponding Lagrangian function is expressed as

$$\begin{aligned} \mathcal{L} = \mathcal{W} + \lambda_E(E_{PV} + E_{DG} - E_A - \textstyle\sum_i E_{H,i} - \gamma_W W_\text{s}) \\ + \lambda_W(\eta_W W_\text{s} - W_A - \textstyle\sum_i W_{H,i}) \\ + \lambda_\text{cap}(\overline{W} - W_A - \textstyle\sum_i W_{H,i}), \end{aligned} \quad (8)$$

where λ_E, λ_W, and $\lambda_\text{cap} \geq 0$ are the dual variables (shadow prices) associated with the energy balance, water balance, and water-availability constraints. These multipliers quantify the marginal welfare improvement from relaxing each constraint and form the foundation for the transactive interpretation of the proposed mechanism.

979-8-3315-8138-1

D. Optimality Conditions and Transactive Interpretation

From the Lagrangian formulation (Eq.(8)), the KKT conditions establish the equilibrium relationships between marginal utilities, productivities, and shadow prices. At the social optimum, all agents equate their marginal valuations to the corresponding shadow prices, ensuring an efficient allocation of resources. For households, the first-order conditions yield $\lambda_E = \alpha_i / E^{\star}_{H,i}$ and $\lambda_W + \lambda_{\text{cap}} = \beta_i / W^{\star}_{H,i}$, implying that the marginal utilities of energy and water consumption equal their respective transactive prices. In the agricultural subsystem, $\lambda_E = p_Y A_0 \phi W_A^{\theta} E_A^{\phi-1}$ and $\lambda_W + \lambda_{\text{cap}} = p_Y A_0 \theta W_A^{\theta-1} E_A^{\phi}$, indicating that energy and water inputs are optimally selected when their marginal productivities match the prevailing energy and water shadow prices. For diesel generation, the optimality condition $\lambda_E = a_{DG} + 2 b_{DG} E^{\star}_{DG}$ ensures that the marginal cost of electricity equals the system energy price. The water–energy coupling condition $\lambda_W = (\lambda_E \gamma_W)/\eta_W$ reflects the physical dependence of usable water on the energy required for pumping. Furthermore, the shadow price λ_E represents the marginal welfare gain of an additional kilowatt-hour and defines the transactive price $p_{\text{WEF}} = \lambda_E$. Similarly, λ_{cap} quantifies the marginal value of relaxing the water-availability constraint, interpreted as the scarcity price $q_W = \lambda_{\text{cap}}$. The total water price thus internalizes both its energetic and scarcity components, $p_W^{\text{tot}} = p_{\text{WEF}} \gamma_W + q_W$, where the first term represents the energy cost of pumping and the second captures the opportunity cost of limited supply. These dual variables $\{\lambda_E, \lambda_W, \lambda_{\text{cap}}\}$ act as transactive signals that decentralize the centralized optimum: a local market in which each agent maximizes its own welfare under prices $\{p_{\text{WEF}}, p_W^{\text{tot}}, q_W\}$ reproduces the same allocation as the social-welfare solution.

In summary, through Lagrangian decomposition, the centralized welfare problem can be interpreted as a price-taking equilibrium where agents respond to token-based prices $(p_{\text{WEF}}, p_W^{\text{tot}})$ that equal their respective marginal costs, ensuring consistency between the social optimum and decentralized coordination. Conceptually, tokens are endogenously issued and cleared by the CC through the internal settlement of resource balances, ensuring budget neutrality at the community level. Their value is anchored to the endogenous shadow price of energy, which provides a non-speculative and scarcity-sensitive reference for decentralized coordination. This mechanism guarantees fairness and consistency across agents, as all households and subsystems face identical marginal prices and cannot be excluded under scarcity conditions.

E. Sensitivity and Opportunity Costs

At the social optimum $\mathcal{W}^{\star}$, obtained from the the dual variables quantify how community welfare (Eq. (4)) responds to marginal changes in resource availability. An additional kilowatt-hour of energy increases $\mathcal{W}^{\star}$ by λ_E; while an extra cubic meter of water raises it by λ_{cap}, when the water cap is binding. Thus, λ_E reflects the value of expanding local generation or efficiency investments managed by the DSO, whereas λ_{cap} measures the benefit of improving water availability. Formally, the partial derivatives of the optimal value function define the corresponding opportunity costs:

$$\frac{\partial \mathcal{W}^{\star}}{\partial \overline{E}_{PV}} = \mu^{+}_{PV} \geq 0, \quad \frac{\partial \mathcal{W}^{\star}}{\partial \overline{W}} = \lambda_{\text{cap}} \geq 0,$$

$$\lambda_E = \frac{\partial \mathcal{W}^{\star}}{\partial (E_{PV} + E_{DG})}.$$

Under the transactive interpretation, these shadow prices function as dynamic coordination signals. Although the *WEF Token* conceptually resembles a local currency, within this framework it operates as a transactive price signal endogenously derived from the welfare optimization problem. By expressing all economic and physical quantities in energy-equivalent units, the *WEF Token* internalizes scarcity relationships and cross-sectoral dependencies, effectively functioning as a floating unit of account and providing a consistent foundation for the multi-scenario analyses presented in the following section.

III. An Illustrative Numerical Example

The proposed framework is applied to a community composed of ten households ($|\mathcal{H}| = 10$), with an available photovoltaic energy of $\overline{E}_{PV} = 15$ kWh/day, and a maximum available water volume of $\overline{W} = 8$ m^3/day. Diesel generation coefficients are $a_{DG} = 0.23$ and $b_{DG} = 0.02$ [USD/kWh, USD/kWh^2], while the pumping subsystem exhibits an efficiency of $\eta_{\text{PS}} = 0.55$ and a specific energy consumption of $\gamma_W = 0.15$ kWh/m^3. The water-use efficiency is set to $\eta_W = 0.9$, and the agricultural productivity coefficient to $A_0 = 1.2$, with elasticities $\theta = 0.4$ and $\phi = 0.3$ for water and energy, respectively. Market reference prices are defined as $p_0 = 0.12$ USD/kWh for electricity, and $p_Y = 0.40$ USD/kg for agricultural products. Household utilities are calibrated based on heterogeneous reference demands. For each household $i \in \mathcal{H}$, the daily reference energy and water demands are $\hat{E}_{H,i} \in [2.5, 6.0]$ kWh/day and $\hat{W}_{H,i} \in [0.18, 0.60]$ m^3/day, respectively. Solving the welfare maximization problem (Eq. (4)) yields an equilibrium with a transactive price of $p_{\text{WEF}} = 0.32$ USD/kWh. The optimal operation allocates 15 kWh/day from PV, 2.2 kWh/day from diesel backup, and 1.3 kWh/day for pumping, resulting in a welfare of 2.28 USD/day (7.1 kWh-eq/day). The shadow prices $\lambda_E = 0.32$ [USD/kWh or tokens/kWh] and $\lambda_W \approx 0.05$ USD/m^3 match the equilibrium prices, confirming KKT consistency. The water scarcity multiplier ($q_W = 0.003$ USD/m^3) indicates that agricultural demand is prioritized without significantly restricting households. A sensitivity analysis is first conducted to evaluate how variations in the availability of PV energy and water affect overall welfare and the resulting transactive price. Based on this calibrated equilibrium, the model is then reformulated in token-equivalent units. The *WEF Token*, defined as an energy-equivalent currency valued at p_{WEF}, serves as a unified reference to normalize all economic variables. This transformation allows a consistent

979-8-3315-8138-1

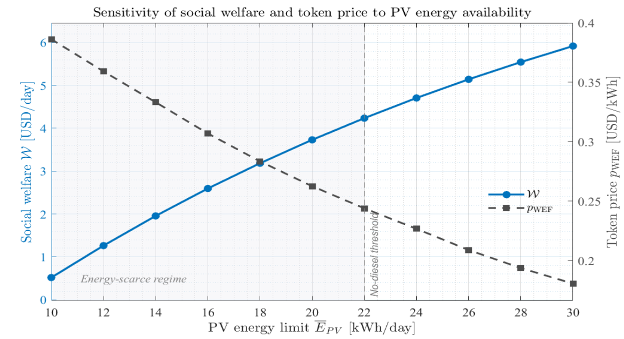
cross-resource comparison of opportunity costs and underpins the scenario-based analyses presented next.

IV. Results and Discussion

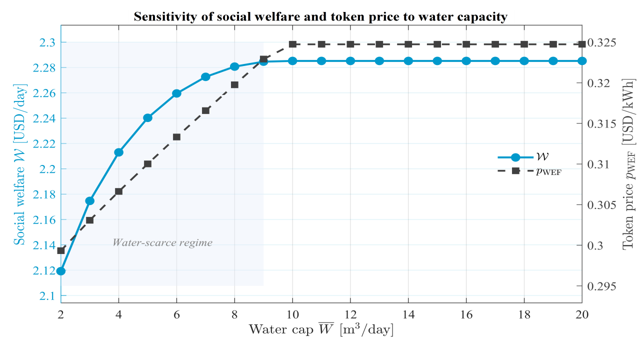
A. Sensitivity Analysis

The sensitivity analysis evaluates the impact of varying available PV energy and water availability on social welfare and transactive price, while all other parameters remain fixed according to the base-case configuration presented in Section III. As shown in Fig. 1(a), social welfare increases as available PV energy rises, while the transactive energy price p_{WEF} decreases accordingly. Under conditions of limited PV energy availability, diesel generation remains active to maintain supply, and welfare remains low, whereas for $\overline{E}_{PV} \geq 22$ kWh/day, where diesel becomes negligible, welfare increases, and p_{WEF} converges toward its lower bound. This inverse relation between p_{WEF} and welfare reflects the expected behavior of a scarcity-based transactive signal: as renewable energy availability increases, the marginal value of electricity declines. Likewise, Fig. 1(b) analyzes the influence of water availability. Welfare rises with $\overline{W}$ up to approximately 9 m^3/day, beyond which it plateaus, indicating hydric sufficiency. During scarcity ($\overline{W} < 8$ m^3/day), the shadow price q_W remains positive, and most of the additional water is allocated to agriculture (food resource), while residential consumption stays nearly constant. Once the constraint becomes non-binding, $q_W \to 0$, confirming that water no longer limits social welfare.

Overall, the sensitivity curves demonstrate that the *WEF Token* mechanism coherently internalizes multi-resource scarcity. In constrained regimes, both p_{WEF} and q_W rise, signaling limited availability and activating backup generation, whereas in abundant conditions, these values fall and the system approaches its welfare optimum.



(a)



(b)

Fig. 1: Sensitivity of social welfare and token price with respect to: (a) Available PV energy; (b) Available water.

B. Scenario Analysis

Building upon the calibrated base case, defined by an available PV energy of 15 kWh/day and a water cap of 8 m^3/day, the equilibrium transactive price $p_{\mathrm{WEF}} = 0.32$ USD/kWh is adopted as the reference energy price p_0. Accordingly, one *WEF Token* represents one kilowatt-hour equivalent valued at p_0 (for the reference scenario S_4). All subsequent analyses are thus expressed in token units, enabling consistent cross-resource comparison and a clear interpretation of opportunity costs within the WEF Nexus framework. The token-based analysis evaluates ten combined PV–water scenarios, denoted as $S_1(10,6)$, $S_2(12,6)$, $S_3(14,10)$, $S_4(15,8)$, $S_5(15,10)$, $S_6(18,10)$, $S_7(18,12)$, $S_8(20,12)$, $S_9(20,15)$, and $S_{10}(25,18)$[kWh/day, m^3/day], where each pair $(\overline{E}_{PV}, \overline{W})$ denotes the available PV energy and water cap, respectively. Fig. 2 compares the token-based daily values of energy, water, food, and total welfare with the corresponding marginal prices of energy and water across the scenarios. The bars represent the total daily value of each resource in tokens/day, obtained from the equilibrium allocation, while the lines depict the scarcity-sensitive transactive prices in tokens per unit. This joint representation links the physical flows of resources with their economic opportunity costs. As photovoltaic available energy $\overline{E}_{PV}$ and water availability $\overline{W}$ increase from S1 to S10, the total welfare $\mathcal{W}$ rises from 1.6 to 15.9 tokens/day, driven mainly by the energy contribution, which grows from about 16.8 to 19.0 tokens/day. Water and food values also increase, from 1.0 to 2.2 tokens/day and 1.6 to 6.0 tokens/day, respectively. Although energy dominates the total value composition (about 75–85%), the share of food becomes increasingly significant at higher resource levels, reflecting the expansion of agricultural production enabled by greater energy and water availability. The marginal prices exhibit the opposite behavior: the energy price p_{WEF} declines from 1.3 to 0.8 tokens/kWh, and the total water price p_W^{tot} decreases 50%, confirming that the WEF token consistently reflects resource scarcity. In low-resource scenarios (S1–S3), both prices are high, signaling limited capacity and higher opportunity costs. As the system approaches resource abundance (S8–S10), these prices stabilize at lower levels, while welfare and agricultural output reach their upper bounds.

To further assess distributional effects, Fig. 3 illustrates the household-level allocation of energy and water across the ten tokenized scenarios. As $\overline{E}_{PV}$ and $\overline{W}$ increase, both resources exhibit a monotonic rise in per-household availability, confirming that the token-based equilibrium reallocates benefits consistently with total capacity growth. During scarcity con-

979-8-3315-8138-1

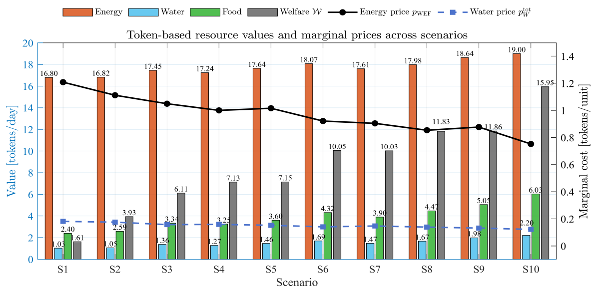


Fig. 2: Token-based marginal values and welfare across scenarios.

ditions (S1–S4), the shadow price $q_W > 0$ indicates that water availability directly constrains community welfare, with most of the incremental resource directed toward agriculture. Thus, the allocations display greater heterogeneity, with certain households receiving up to 30% less energy or water than the average. Beyond the sufficiency threshold ($\overline{E}_{PV} \geq 20$ kWh/day and $\overline{W} \geq 10$ m^3/day), distributions become more homogeneous, and the average allocations stabilize around 2.5 kWh/day and 0.18 m^3/day per household.

In summary, the results confirm that the *WEF Token* serves as a unified valuation and coordination mechanism that links physical resource flows to social welfare. When energy or water are scarce, marginal prices rise and welfare remains constrained; as capacities expand, prices decline and welfare increases, with food gaining greater relevance in the overall value composition. This dual role translates optimization outputs into interpretable market indicators, providing a quantitative tool for assessing how variations in resource availability or infrastructure influence welfare and opportunity costs within sustainable WEF communities. Future extensions will incorporate minimum-service constraints to ensure equitable resource access among households under scarcity, thereby reflecting social-policy considerations in community-scale markets. Additionally, due to the daily temporal aggregation adopted in the numerical analysis, short-term effects such as photovoltaic intra-day intermittency or time-of-use scarcity events are not explicitly represented and constitute an important limitation of the current formulation.

V. Conclusions

This work introduced a WEF–Transactive Framework that unifies energy, water, and food management through welfare optimization and transactive pricing. The *WEF Token* enables a common energy-equivalent representation, linking scarcity, opportunity costs, and welfare across resources. Sensitivity analyses showed that greater PV and water capacities increase welfare and reduce token prices, illustrating the shift from scarcity-limited to renewable-dominant equilibria. Energy remains the primary driver of value, while water and food gain importance with agricultural productivity. Future work will extend the model to a dynamic formulation with hourly resolution and storage integration to capture temporal variability and operational flexibility.

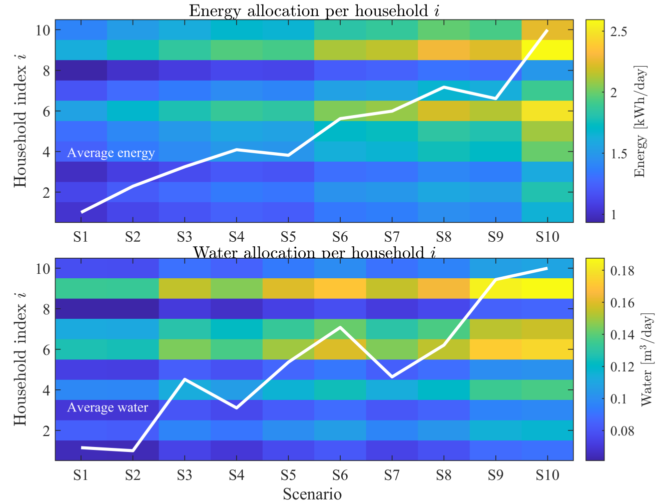


Fig. 3: Energy (top) and water (bottom) allocation per household across scenarios.

References

[1] T. G. A. Council, "Gridwise transactive energy framework version 1.1," tech. rep., GridWise Architecture Council, 2019.

[2] A. H. Tariq and U. Amin, "Peer-to-peer multi-energy trading in a decentralized network: A review," *Renewable and Sustainable Energy Reviews*, vol. 208, p. 114969, 2025.

[3] S. Ghaemi and A. Anvari-Moghaddam, "Local energy communities with strategic behavior of multi-energy players for peer-to-peer trading: A techno-economic assessment," *Sustainable Energy, Grids and Networks*, vol. 34, p. 101059, 2023.

[4] E. M. Biggs, E. Bruce, B. Boruff, J. M. Duncan, J. Horsley, N. Pauli, K. McNeill, A. Neef, F. Van Ogtrop, J. Curnow, B. Haworth, S. Duce, and Y. Imanari, "Sustainable development and the water–energy–food nexus: A perspective on livelihoods," *Environmental Science & Policy*, vol. 54, pp. 389–397, 2015.

[5] X. Cai, K. Wallington, M. Shafiee-Jood, and L. Marston, "Understanding and managing the food-energy-water nexus – opportunities for water resources research," *Advances in Water Resources*, vol. 111, pp. 259–273, 2018.

[6] C. Zhang, X. Chen, Y. Li, W. Ding, and G. Fu, "Water-energy-food nexus: Concepts, questions and methodologies," *Journal of Cleaner Production*, vol. 195, pp. 625–639, 2018.

[7] B. A. MagalhÃ de Aguiar Oliveira, "La moneda social Palmas, viejos instrumentos, nuevas soluciones: Un análisis sociológico del dinero," *Psicoperspectivas*, vol. 19, pp. 68 – 80, 07 2020.

[8] D. Anto, A. Mehta, and A. Murti, "Using energy as a community currency for sustainable development of newly electrified communities," *Energy for Sustainable Development*, vol. 83, p. 101558, 2024.

[9] A. Michel and M. Hudon, "Community currencies and sustainable development: A systematic review," *Ecological Economics*, vol. 116, pp. 160–171, 2015.

[10] G. Seyfang and N. Longhurst, "Growing green money? mapping community currencies for sustainable development," *Ecological Economics*, vol. 86, pp. 65–77, 2013. Sustainable Urbanisation: A resilient future.

[11] M. Mihaylov, S. Jurado, N. Avellana, K. Van Moffaert, I. M. de Abril, and A. Nowé, "Nrgcoin: Virtual currency for trading of renewable energy in smart grids," in *Proceedings of the 11th International Conference on the European Energy Market (EEM14)*, pp. 1–6, 2014.

[12] A. Mas-Colell, M. D. Whinston, and J. R. Green, *Microeconomic Theory*. Oxford University Press, 1995.

[13] S. A. Hatirli, B. Ozkan, and C. Fert, "An econometric analysis of energy input–output in turkish agriculture," *Renewable and Sustainable Energy Reviews*, vol. 9, no. 6, pp. 608–623, 2005.

979-8-3315-8138-1