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Hierarchical transactive home energy management system groups coordination through multi-level consensus sharing-based distributed ADMM ☆

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ABSTRACT

Coordinating residential building groups requires a hierarchical structure in which aggregate objectives and coupled constraints are incorporated into decision-making processes at different layers of the electric distribution system. Failure to handle these matters can raise issues, such as rebound peaks and contingencies. This paper proposes a Hierarchical Transactive Coordination Mechanism (HTCM) capable of dealing with residential consumers' objectives/constraints and local and grid coordinators' shared objectives/coupled constraints under a bottom-up strategy. Particularly, the proposed multi-level framework distributes local and grid coordinators' shared objectives among consumers to flatten the aggregate consumption profile and minimize the aggregate energy cost at each level. The suggested scheme is enhanced by developing two additional operations. A gain-sharing technique is designed to fairly divide the total gain acquired by the grid coordinator across the hierarchy from higher to lower levels, successively. Besides, a coupled constraint-sharing method is devised to link these levels and fulfill the coupled constraints by revising consumers' decisions. The proposed approach is applied to a society of buildings comprising Home Energy Management System (HEMS) groups with demand response-enabled electric Baseboard Heaters (BHs), and its effectiveness is investigated through different case studies. The results demonstrate that the recommended HTCM is able to improve the society's aggregate power profile load factor by 89%, from 0.45 up to 0.85, and decreases its overall electricity cost by 6.2%.

1. Introduction

The increasing demand for energy and the pressing need to reduce carbon emissions [1,2] have led to a growing interest in residential buildings' (consumers) participation in grid services through Demand Response (DR) programs [3,4] and Home Energy Management Systems (HEMSs) [5]. Generally, a DR practice manipulates residential electricity consumption in response to electricity prices/incentives during peak hours. However, uncoordinated participation of HEMSs in such an operation can precipitate excessive demand penetration in the electric distribution grid and, consequently, cause rebound peaks, instabilities, and contingencies [6]. Accordingly, the coordination concept is suggested that can regulate the involvement of single or multiple groups of HEMSs in a DR program with the aim of avoiding these issues.

1.1. Motivation

Modern HEMSs can be designed by coordinating their individual decision-making processes. The coordination manages such innovative systems to act unitedly and achieve individual objectives while respecting shared objectives. Different approaches to coordinating HEMSs in one residential building group have been summarized in [7]. The coordination practice can be adopted by existing smart home technologies such as Hilo by Hydro-Québec [8], OpenADR by Berkeley Lab [9], and Pando by Lo3energy [10]. Coordinating HEMSs can relieve stress on residential area networks and handle local challenges. Coordination serves consumers by meeting their desires and benefits the distribution system operator by fulfilling shared objectives. Objectives can be specified individually to minimize the electricity cost

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Nomenclature

Acronyms

HEMS	Home Energy Management System
HTCM	Hierarchical Transactive Coordination Mechanism
BH	Baseboard Heater
ADMM	Alternating Direction Method of Multipliers

Parameters

α, β, γ	Thermal coefficients
δ	Daily comfort levels (modes) profile
δ_{set}	Comfort set
π	Electricity price
cr	Coordination level
H	Horizon length
N_{CR}	Number of local coordinators (groups)
N_{GCR}	Number of grid coordinators (society)
N_H	Number of houses (consumers in one group)
T^{comf}	Desired indoor temperature
$T^{\min}$ and $T^{\max}$	Minimum & maximum allowable indoor temperatures
T^{sp}	Indoor temperatures allowable range
T_{out}	Outdoor temperature
T^{comf}_{set}, $P(T^{\mathrm{comf}})$	Desired indoor tempe distribution
T^{sp}_{set}, $P(T^{\mathrm{sp}})$	Indoor tempe allowable range distribution
U^{H}_{max}	Maximum household energy usage
$U^{RG_j}_{max}$	Residential group j s maximum capacity
U^{S}_{max}	Maximum energy capacity of society S
$u^{BH,\min}$, $u^{BH,\max}$	Minimum & maximum BH energy
$u^{T,\min}$, $u^{T,\max}$	Minimum and maximum house total energy profile limit
$\delta_{\min}, \delta_{\max}$	Minimum & maximum comfort levels (modes)

Indices and Sets

LG	Exchanged variables (between lower and upper levels) index
$\mathbb{S}_{\mathrm{f}}, \mathbb{S}_{\mathrm{g}}$	Societies set f & g
$\mathbb{RG}_{\mathbb{l}}, \mathbb{RG}_{\mathrm{m}}$	Residential groups set l & m
G	Grid-Level variables index
i	House's index
j	Group/coordinator's index
k	Iteration's index
$\mathcal{H}$	Horizon set
h	Time-slot
RG	Residential group
S	Society
L	Local-Level (group) variables index

Variables

u	House's optimal decision (ADMM)
Z	Global variables averaged (ADMM)
$\overline{Z}$	Global variables averaged (ADMM)
λ	Dual variables (ADMM)
T	Indoor temperature
$\mathrm{u}^{T}_{ji}(h)$	Household i energy at time-slot h in group j
u^{BH}	Electric BH energy usage
u^{FL}	Fixed load demand
u^{T}	Household total energy consumption

Functions

d	Inhabitants discomfort function
F^{ind}_{i}	Individual objectives
F^{shr}	Shared objective

and maximize consumers' comfort. Besides, shared objectives can be set to flatten aggregate profile, enable transactive energy management, modify generation and consumption patterns, decrease reverse power flow, regulate distributed generations, enhance service reliability, and improve grid efficiency [6,7].

Coordination in one residential building group is not sufficient to mitigate challenges at different layers of the distribution system. Particularly, it cannot incorporate coupled constraints between upper and lower levels of the grid, e.g., transformer's maximum energy capacity, essential for harnessing its flexibility at full potential. Moreover, this operation does not deal with collective gain resulting from the united action of individual groups, thus, fails to measure their contribution to the targeted service, i.e. DR. In a market, such uni-level procedures yield lower incomes for their HEMS participants due to the lack of in-between cooperation. In addition, the distribution system cannot be managed effectively with a centralized coordination process due to computational complexity related to integrating many consumers. These issues stimulate the development of multi-level schemes to perform the coordination concept for groups of HEMSs. Such structures enable the coordination of at least the grid-related entity at the upper level (the grid coordinator) and local residential building groups at the lower level. The upper-level coordinator tries to regulate the lower-level coordinators managing smart houses in their groups. These frameworks can specifically assist the distribution grid operator in cold regions like Quebec with managing Baseboard Heaters (BHs) since their remarkable demand can become an emergency operation [11].

1.2. Contribution

This study aims to address the aforementioned issues by proposing a Hierarchical Transactive Coordination Mechanism (HTCM) to practice HEMS groups coordination. Consequently, it brings about the following contribution.

- Designing a hierarchical transactive HEMSs coordination to coordinate DR-enabled EHSs in a society that comprises multiple residential groups. The approach includes a mechanism to share society's objectives among residential groups and, subsequently, distribute groups' shared objectives among HEMSs. The proposed operation satisfies society's and groups' shared objectives and individual objectives as well. Society's objectives are realized to solve the upper-level grid challenges, including aggregate profile load factor improvement and overall energy cost minimization. Besides, group objectives are dealt with to solve the lower-level grid issues comprising load factor improvement and overall energy cost minimization. The coordination leads to complementary actions of groups and consumers.
- Developing a procedure to distribute society's coupled constraints among residential groups' coordinators and, subsequently, broadcast residential groups' coupled constraints among their corresponding HEMSs. This process links the upper and lower levels and satisfies society's and groups' constraints such as the maximum energy capacity.

- Constructing a gain-sharing scheme to distribute society's total gain among residential groups and, in turn, divide each group's total gain among its associated members. The gain-sharing method measures each consumer's contribution and allocates shares in a fair manner.

The rest of this paper is organized as follows: Section 2 provides a comprehensive overview of the existing methodologies employed in the coordination of HEMSs within both single group and multiple groups cases as documented in the literature. Section 3 discusses the proposed system and its associated models of the society, residential groups, electricity prices, residential buildings, and consumers' behavior. Problem formulation and suggested hierarchical transactive HEMSs coordination are presented in Section 4. Section 5 explains the recommended mechanism for sharing society's and groups' coupled constraints among consumers. Section 6 describes the designed technique for distributing the gain among households fairly. The performance of the proposed methods is evaluated in Section 7, followed by conclusions in Section 8.

2. Background

The literature proposes approaches for the coordination of one or multiple HEMSs groups. [6,7,12–21] studied the uni-level coordination for one HEMSs group. Merely coordinating HEMSs within a single residential group is insufficient for resolving challenges that exist across various levels of the distribution system. Safdarian et al. [6] analyzed decentralized coordinated demand responses to prevent rebound peaks. The authors in [7] reviewed the critical matters and the latest research on coordinated HEMSs in one residential group. They proposed effective frameworks to make the idea of HEMSs coordination feasible. [12] coordinated consumers' batteries in a community to minimize the aggregate coalitional energy cost. Nucleolus and Shapley games were used to form the coalitions and pick the optimal one. Nevertheless, the strategy includes a large amount of computation in a centralized entity. [13] modeled rational consumers' behavior in a group through a non-cooperative Nash game and proposed a price policy to coordinate households' storage devices. However, the coupled constraints were not shared among consumers. [14] developed an energy management system in the distribution sector based on forming coalitions between consumers and maximizing each coalition's payoff. [15] practiced a decentralized indirect HEMS coordination (direct or indirect coordination is explained by [16]) in a residential community by characterizing aggregate consumption through generating a dynamic price. [16] designed a HEMSs coordination mechanism with demand response-enabled thermostats for a single residential group. Notwithstanding, the authors searched for a coordination process that met the individual/shared objectives and used the shared ones to solve the residential group challenges including the total energy cost minimization and load factor improvement. The mechanism can be developed through a multi-level framework that deals with the local grid challenges in different layers of the distribution system considering upper-level constraints in the HEMS's decision-making. [17] established a distributed home energy management in a microgrid. [18] proposed a distributed dynamic price-based demand response program to coordinate electric thermal storage systems in a residential group indirectly. The suggested technique can be developed by sharing team objectives between agents and adding complementary decision-making among consumers. [19] formulated a multi-objective optimization problem for optimal load scheduling in a cluster of buildings through a multi-agent system. [20] suggested coordination methods for managing distributed prosumers and fleets of electric vehicles. [21] introduced a Pareto-based approach that incorporates equilibrium-based decision-making for addressing multi-objective optimization challenges in handling multiple home energy management systems.

Other research studies investigated multi-level or hierarchical coordination of microgrids or HEMS groups. Notwithstanding, relevant works on this subject primarily focused on exploring the coordination between multiple microgrids or groups without taking into account the decision-making process of consumers [22–31]. [23] coordinated several energy hubs in a community through a bargaining game. Players bargained with the utility and other players to trade energy at the negotiated price. [24] presented a leader-follower Stackelberg game to model the coordinated energy management of multiple microgrids. The objectives of each microgrid and energy market operator were considered. However, the individual objectives of each consumer were neglected. [25] established transactive energy management in a macro-grid comprising multiple micro-grids through a hierarchical optimization as a multi-leader–multi-follower Stackelberg game. The authors set the seller and buyer groups in terms of leaders and followers, respectively. However, the consumer's decision-making process was not investigated in the game directly. [26] suggested a bi-level Stackelberg game among multiple microgrids (followers) and the distribution network operator (leader) for operating an economic dispatch. However, the coordinated optimization of consumers in each microgrid was not investigated. [27] established an energy management coordination among microgrids through a bi-level optimization. However, consumers' decision-making processes and their transactive contributions to the coordination were not fully considered. [28] executed a distributed coordination framework for microgrids. Likewise, consumers' local optimization (the decision-making process) was not dealt with. [22] presented a distributed framework based on the Analytical Target Cascading (ATC) algorithm to coordinate energy exchanges between multiple microgrids. However, the consumers' decision-making process was not considered. Similarly, [29–31] investigated the coordinated operation of multiple microgrids without modeling consumers' decision-making process.

Various analyses were conducted on the coordination among multiple microgrids or groups considering the decision-making process of consumers [32–36]. However, these studies did not consider distributing the total gain, shared objectives, coupled constraints, and complementary action of players. [32] designed a centralized, hierarchical HEMSs coordination through a three-level optimization framework. The optimization included HEMSs coordination in the low-voltage grid (lower level) and a Volt/VAR regulation in the medium-voltage grid (upper level). [33] developed a multi-leader–multi-follower Stackelberg game through a multi-level framework to model the interaction among residential microgrids (leaders) and consumers (followers). The framework included a cooperative game among leaders and a non-cooperative game between consumers in each group. [34] explored a Stackelberg game among utility companies as leaders to maximize their gain and consumers as followers to satisfy their welfare in microgrids. The price generated based on the competition among utility companies indirectly coupled consumers at the lowest level and power generators at the highest level. Anoh et al. [35] realized a Stackelberg game between producers and consumers in a grid. [36] modeled coordinated energy management among consumers, microgrids, and a microgrid cluster through a hierarchical Stackelberg game. The game optimization comprised upper and lower levels. As the leader in the upper-level game, the microgrid cluster agent generated a price to coordinate microgrids as followers and microgrid agents tried to maximize their profit. Microgrid agents in the lower-level game led consumers by updating selling prices according to their energy profiles. Consumers, as followers, revised their consumption profile accordingly. [37] introduced a decentralized control strategy for coordinating a diverse array of residential thermal energy storage systems, taking into account operational constraints at national and local levels. The proposed iterative coordination algorithm optimizes storage schedules based on real-time electricity prices, yielding substantial cost savings for individual participants and the overall system, and effectively managing distribution network restrictions.

Most of the above research did not formulate the link between consumers' decisions at the lowest level with local coordinators of

Table 1
Comparison of the related works with the proposed hierarchical coordination.

References	Study field	Topology	Techniques	Multi-level group coordination	Coupled constraint sharing	Heating system	Decomposition techniques	Multi-level gain sharing	Complementary actions
[6]	Bi-level HEMSs	Distributed	Upper subproblem sets value for lower subproblems	✗	✗	✗	✗	✗	✗
[16]	HEMSs coordination	Distributed	Consensus and sharing team objectives	✗	✗	✓	CS-ADMM	Uni-level gain sharing	✓
[22]	Microgrids coordination	Distributed	Robust optimization	Lacking consumer decision-making	✗	✗	Analytical target cascading	✗	✗
[12]	HEMSs coalitions	Centralized	Shapley game and balanced game to find optimal coalition	✗	✗	✗	✗	Uni-level gain sharing	✗
[13]	DR coordination	Distributed	Nash game (non-cooperative)	✗	✗	✗	✗	✗	✗
[14]	Energy cell groups coalitions	Centralized	Make coalitions	✗	✗	✗	✗	✗	✗
[15]	HEMSs coordination	Distributed	Dynamic price and negotiation	✗	✗	✗	✗	✗	✗
[32]	HEMSs coordination	Centralized	Hierarchical three-level optimization framework	✓	✗	✓	✗	✗	✗
[23]	Cooperative energy hubs	Distributed	Nash bargaining game; and Pareto optimality	Lacking consumer decision-making	✗	✗	ADMM	✗	✗
[24]	Microgrids coordination	Distributed	Stackelberg game	Lacking consumer decision-making	✗	✗	✗	✗	✗
[25]	Microgrids coordination	Distributed	Stackelberg game (multileader–multifollower)	Lacking consumer decision-making	✗	✗	✗	✗	✗
[33]	HEMSs coordination	Distributed	Stackelberg game (multileader–multifollower)	✓	✗	✗	✗	✗	✗
[34]	DR coordination	Distributed	Stackelberg game (multileader–multifollower)	✓	✗	✗	✗	✗	✗
[26]	Microgrids coordination	Distributed	Stackelberg game (unileader–multifollower)	Lacking consumer decision-making	✗	✗	✗	✗	✗
[27]	Microgrids coordination	Distributed	Hierarchical Stackelberg game	Lacking consumer decision-making	✓	✗	✗	✗	✗
[36]	Microgrids coordination	Distributed	Hierarchical Stackelberg game	✓	✗	✗	✗	✗	✗
[28]	Microgrids coordination	Distributed	MPC-based optimization	Lacking consumer decision-making	✗	✗	Accelerated distributed augmented Lagrangian	✗	✗
Proposed approach	**HEMS groups coordination**	**Distributed**	**Multi-level consensus and sharing (team objectives /coupled constraints)**	✓	✓	✓	**Multi-level CS-ADMM**	✓	✓

each group at the intermediary level and the grid coordinator at the highest level, which manages local ones. The cooperative, hierarchical optimization among agents (consumers, local coordinators, and the grid coordinator) at different levels requires further investigation. Accordingly, consumers should be involved in any developed transactive framework. Besides, the link between upper and lower levels should be analyzed by sharing upper-level constraints/objectives with the lower levels. Therefore, this paper links consumers' decisions at the lowest level with local and grid coordinators at the intermediary and highest levels, respectively.

Table 1 highlights the current study's contributions compared to relevant ones in the literature. The comparison is made from the viewpoint of the case study, topology, technique, coordination structure, constraint-sharing, targeted demand, problem decomposition, gain-sharing, and complementary action.

3. System framework and model

Fig. 1 illustrates a society of coordinated consumers (HEMSs) that includes N_{CR} local coordinators and one grid coordinator. Each local coordinator manages N_H houses located in the same residential group n_{CR}. The coordination among N_{CR} local coordinators is processed by the grid coordinator n_{GCR}. Besides, each aggregator is connected to N_{GCR} grid coordinators. Fig. 1 represents the topology that has been used to implement the proposed hierarchical multi-Level coordination technique. As shown in Fig. 1, this work studies the hierarchical coordination process in society and elaborates on interactions among consumers, local coordinators, and the associated grid coordinator.

3.1. Time horizon

In this work, the time horizon length is 24 h, and 10 min has been chosen as the sampling time. Consequently, the time horizon length has been represented by $H = 144$, and the time-slot h can take any integer value from 1 to 144 as illustrated by horizon set $\mathcal{H} = [1, H]$.

3.2. Residential load models

This study models houses' thermal parameters, fixed loads daily stochastic consumption profiles, and consumers' preferences using experimental data from single-family detached houses located in Trois-Rivières, Québec, Canada. Each house possesses BHs governed by PID-based thermostats. The indoor temperature, outdoor temperature, set-points, and heaters' energy consumption have been measured and recorded from January to April 2018. Each household possesses schedulable (flexible) and non-schedulable (fixed) loads. The BHs are considered as households' flexible loads. BHs are controlled by intelligent thermostats to satisfy consumers' preferences. Preferences are modeled using comfort levels and desired set points across the day. They characterize household flexibility levels for participating in a DR program. Besides, fixed loads cannot be scheduled and are modeled based on household activities, occupancy, and usual energy consumption habits. Fixed load's daily stochastic consumption profiles are modeled by exploiting the experimental data from relevant appliances. The total consumption profile of each household can be modeled as,

$$u^T(h) = u^{BH}(h) + u^{FL}(h), \quad (1)$$

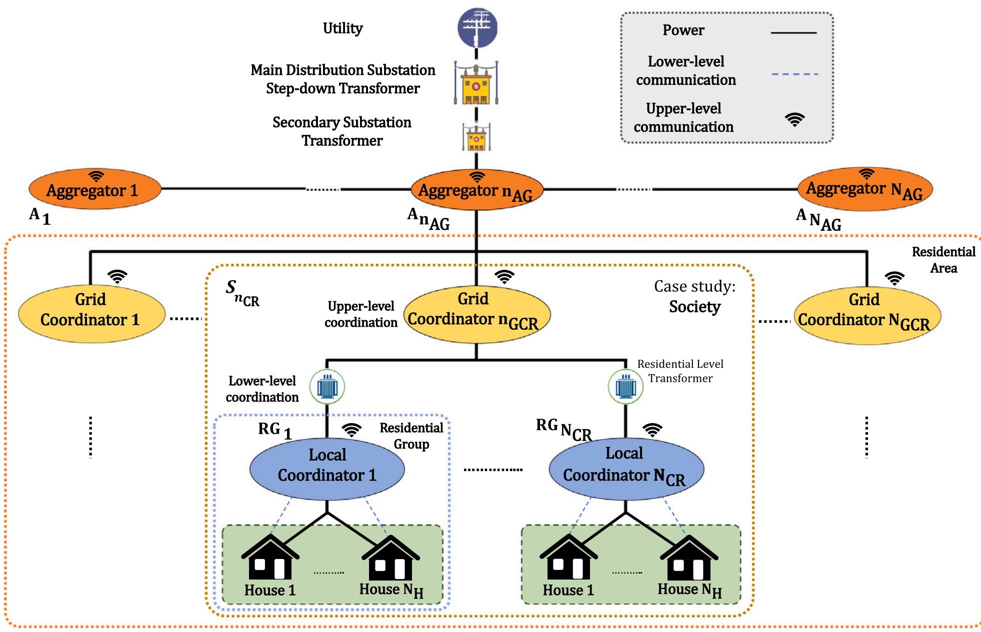


Fig. 1. The block diagram of the coordinated society of consumers.

where u^T stands for household total energy consumption, u^{BH} states electric BH energy usage, and u^{FL} represents fixed load demand. The following linear thermal model, employed in various Refs. [16,38,39], describes the dynamic of the household's BH system.

$$T(h+1) = \alpha T(h) + \beta u^{BH}(h) + \gamma T_{out}(h), \tag{2}$$

that α, β, and γ present the thermal coefficients parameters. T expresses the indoor temperature, T_{out} represents the outdoor temperature, and h depicts the time. The dependency of the indoor temperature in time-slot $h+1$ on the indoor temperature, the BH energy profile, and the outdoor temperature in time-slot h has been defined by α, β, and γ, respectively. The ridge regression technique has been applied to the experimental data to estimate the thermal parameters α, β, and γ for all the houses. Various types of dwellings are considered with different characteristics such as size (areas), pool heaters, spa, the number of occupants, thermostats, floors, and rooms to promote a feasible analysis.

3.3. Inhabitants' discomfort

The inhabitants' discomfort function [16,40] of each household is modeled by (3).

$$d(h) = \delta\big(T^{\text{comf}(h)} - T(h)\big)^2, \tag{3}$$

where d represents their discomfort, the term T^{comf} defines the desired indoor temperature, and δ stands for the comfort levels during the day. d, T, T^{comf}, and δ are vectors with length H. Inhabitants select δ from the set $\delta_{set} = \{\delta_{\min}, \delta_{\max}\}$ to choose between economic mode or comfort mode for each time-slot. $\delta_{\max}$ expresses that inhabitants are interested in comfort mode and getting close to the set point. On the contrary, $\delta_{\min}$ denotes that occupants are interested in economic mode and the indoor temperature can be different from the set-point. Each HEMS agent adjusts the indoor temperature while respecting the constraints,

$$T \in [T^{\min}, T^{\max}], \tag{4}$$

$$T^{\min} = T^{\text{comf}} - T^{\text{sp}}, \tag{5}$$

$$T^{\max} = T^{\text{comf}}, \tag{6}$$

$$\delta_{\min} = 0, \tag{7}$$

$$u^{BH} \in [u^{BH,\min}, u^{BH,\max}], \tag{8}$$

$$u^T \in [u^{T,\min}, u^{T,\max}], \tag{9}$$

that $T^{\min}$ and $T^{\max}$ represent minimum and maximum allowable indoor temperatures, respectively. T^{sp} represents the difference between minimum and maximum allowable indoor temperatures. $u^{BH,\min}$ and $u^{BH,\max}$ symbolize minimum and maximum acceptable BH energy, respectively. $u^{T,\min}$ and $u^{T,\max}$ stand for minimum and maximum allowable household energy, respectively. The indoor temperature set-point range for the winter season has been characterized using historical data supplied by Canadian Center for Occupational Health and Safety. This range is $20-23$ °C. The distribution of T^{sp}, T^{comf}, and δ for building a stochastic consumers' preferences set have been modeled based on the experimental data from our previous studies [16,41]. As defined by (10), T^{sp} can take random values from the set T^{sp}_{set} in C^o with the probabilities $P(T^{\text{sp}})$. Besides, T^{comp} can take random values from the set T^{comf}_{set} in degree Celsius (C^o) with the probabilities $P(T^{\text{comf}})$.

$$T^{\text{comf}} \in T^{\text{comf}}_{set} = \{20, 21, 22, 23\}[C^o], \tag{10}$$

$$P(T^{\text{comf}}) = [0.1, 0.3, 0.5, 0.1][C^o] \tag{11}$$

$$T^{\text{sp}} \in T^{\text{sp}}_{set} = \{1, 2, 3, 4\}[C^o], \tag{12}$$

$$P(T^{\text{sp}}) = [0.1, 0.3, 0.4, 0.2][C^o] \tag{13}$$

The maximum comfort level (δ_{max}) is generated randomly by using a log-normal distribution with the following variance and expectation,

$$Var(\delta_{\max}) = 1, \quad \mathbb{E}(\delta_{\max}) = 5, \tag{14}$$

3.4. Residential group and society

This work conceptually divides the distribution system into three levels and names them as follows: residential group, society, and residential area. As illustrated in Fig. 1, each residential area consists of N_{GCR} societies (grid coordinators), each society possesses N_{CR} residential groups (local grid coordinators), finally, each residential group includes N_H households. This study focuses on the hierarchical coordination in society and considers that each residential group comprises maximum of 15 houses ($N_H = 15$). Each residential group belongs to only one society, and each house is part of only one residential group. For instance, there are no shared elements (residential groups) between the society set $\mathbb{S}_{\mathbb{f}} := \{RG_1, \ldots, RG_{N_{CR,f}}\}$ and the society set $\mathbb{S}_{\mathbb{g}} := \{RG_1, \ldots, RG_{N_{CR,g}}\}$. Similarly, there are no common elements (houses) between the group set $\mathbb{RG}_{\mathbb{l}} := \{H_1, \ldots, H_{N_{H,l}}\}$ and the group set $\mathbb{RG}_{\mathbb{m}} := \{H_1, \ldots, H_{N_{H,m}}\}$, as illustrated below.

$$\mathbb{S}_{\mathbb{f}} \cap \mathbb{S}_{\mathbb{g}} = \emptyset, \quad \forall f \neq g, \tag{15}$$

$$\mathbb{RG}_{\mathbb{l}} \cap \mathbb{RG}_{\mathbb{m}} = \emptyset, \quad \forall l \neq m, \tag{16}$$

where $\mathbb{S}_{\mathbb{f}}$, $\mathbb{S}_{\mathbb{g}}$, $\mathbb{RG}_{\mathbb{l}}$, and $\mathbb{RG}_{\mathbb{m}}$ sets denote society f, society g, residential group l, and residential group m, respectively. Each society set is composed of residential groups as its elements, while each group set consists of houses as its elements. The aggregate energy of residential groups in society S should fulfill the society's capacity constraint as (17), the aggregate energy of households in the residential group RG_j should meet the group's capacity constraint as (18), and total energy profile of each household fulfills the maximum limit as (19).

$$\left| \sum_{j=1}^{N_{CR}} \sum_{i=1}^{N_H} u_{ji}^T(h) \right| \leqslant U_{max}^S, \tag{17}$$

$$\left| \sum_{i=1}^{N_H} u_{ji}^T(h) \right| \leqslant U_{max}^{RG_j}, \tag{18}$$

$$\left| u_{ji}(h) \right| \leqslant U_{max}^H, \tag{19}$$

that $u_{ji}^T(h)$ symbolizes the total energy of household i at time-slot h in the residential group j, which belongs to society S. U_{max}^S is maximum energy capacity of society S. $U_{max}^{RG_j}$ defines residential group j's capacity constraint, and U_{max}^H stands for maximum household energy use. The aforementioned constraints determine the society's and residential groups' upper bound on energy capacity.

4. Problem formulation and proposed HTCM

This section unfolds a series of pivotal steps in crafting the proposed HTCM. It commences by instituting a centralized, uncoordinated energy management system within a society, elucidating consumers' distinct objectives. This is followed by formulating the society's centralized coordination problem and introducing shared objectives. Additionally, a centralized uni-level coordination problem specific to a residential group is defined. The section then transitions into the distributed implementation of the centralized uni-level coordination in the residential group. Lastly, it ventures into crafting a society-level hierarchical multi-level coordination structure, addressing both lower-level and upper-level coordination problems.

4.1. Centralized problem

In the centralized uncoordinated energy management scenario, the individual problems for each house i (HEMS agent), the centralized problem for each residential group j (local coordinator agent), and the centralized problem for the entire society S are formulated as (20)–(22).

$$\begin{aligned} &\underset{u_{ji}^T}{\text{minimize}} \quad \sum_{h=0}^{H} \left[\pi u_{ji}^T(h) + d_{ji}(h) \right], \\ &s.t.: \ (1)\text{–}(19) \backslash \{(15), (16), (17), (18)\}, \end{aligned} \tag{20}$$

$$\begin{aligned} &\underset{u_{ji}^T}{\text{minimize}} \quad \sum_{i=1}^{N_H} \sum_{h=0}^{H} \left[\pi u_{ji}^T(h) + d_{ji}(h) \right], \\ &s.t.: \ (1)\text{–}(19) \backslash \{(15), (17)\}, \end{aligned} \tag{21}$$

$$\begin{aligned} &\underset{u_{ji}^T}{\text{minimize}} \quad \sum_{j=1}^{N_{CR}} \sum_{i=1}^{N_H} \sum_{h=0}^{H} \left[\pi u_{ji}^T(h) + d_{ji}(h) \right], \\ &s.t.: \ (1)\text{–}(19), \end{aligned} \tag{22}$$

where π denotes the electricity price, which is the highest tariff of Hydro-Québec's fixed Rate D [42] (domestic and household consumers), equal to 10 ¢/kWh. The problem (20) minimizes each household electricity bill and maximizes the inhabitants' comfort. The Eq. (21) guarantees efficiency and comfort in a residential group. Finally, bill minimization and comfort maximization of all households located in the society are assured in (22). The problem (22) only satisfies all households' individual (selfish) objectives and makes no attempt to consider any shared objectives in the society. However, shared objectives can be considered and designed in society to mitigate the local grid challenges and relieve the stress on the distribution system. In this work, social challenges are improving society's aggregated profile's load factor and minimizing aggregate consumption. Therefore, supplementary society's objectives are designed and added to (22) in order to solve the society's challenges. The Eq. (22) can be reformulated to represent the society's centralized energy management coordination problem as follows,

$$\begin{aligned} &\underset{u_{ji}^T}{\text{minimize}} \quad \sum_{j=1}^{N_{CR}} \sum_{i=1}^{N_H} \sum_{h=0}^{H} \left[\pi u_{ji}^T(h) + d_{ji}(h) \right] \\ &+ \left\| \sum_{j=1}^{N_{CR}} \sum_{i=1}^{N_H} u_{ji}^T - \left(\sum_{h=0}^{H} \frac{\sum_{j=1}^{N_{CR}} \sum_{i=1}^{N_H} u_{ji}^T(h)}{H} \right) \right\|_2^2 \\ &+ \left\| \sum_{h=0}^{H} \sum_{j=1}^{N_{CR}} \sum_{i=1}^{N_H} u_{ji}^T(h) \right\|_2^2, \\ &\quad s.t.: \ (1)\text{–}(19), \end{aligned} \tag{23}$$

The first term in (22) states the individual objectives (F^{ind}) of each agent. The term $\left\| \sum_{j=1}^{N_{CR}} \sum_{i=1}^{N_H} u_{ji}^T - \left(\sum_{h=0}^{H} \frac{\sum_{j=1}^{N_{CR}} \sum_{i=1}^{N_H} u_{ji}^T(h)}{H} \right) \right\|_2^2$ guarantees society's aggregate profile flatness and improves its load factor. The term $\left\| \sum_{h=0}^{H} \sum_{j=1}^{N_{CR}} \sum_{i=1}^{N_H} u_{ji}^T(h) \right\|_2^2$ minimizes the total consumption during the day in the society. These terms encompass the shared objectives (F^{shr}).

In the centralized case, the utility makes decisions on behalf of households to schedule their flexible assets. As elaborated in Section 1, this work considers interactions among agents to design a hierarchical multi-level HEMSs coordination through a distributed optimization and a decision-making framework.

4.2. Residential group distributed uni-level coordination

The centralized uni-level energy management coordination problem for one residential group, involving N_H HEMSs agents, utilizes centralized consensus and sharing ADMM-based techniques [16]. This scenario can be expressed with agents local variables u_i and a common global variable $\overline{Z}$ in the residential group through (24) to satisfy individual (F_i^{ind}) and shared (F^{shr}) objectives.

$$\begin{aligned} &\underset{u_i \ \& \ \overline{Z}}{\text{minimize}} \quad \sum_{i=1}^{N_H} F_i^{ind}(u_i) + cr \ F^{shr}(N_H \overline{Z}), \\ &s.t.: \ \overline{Z} = \left(\frac{1}{N_H}\right) \sum_{i=1}^{N_H} z_i \ \& \ u_i - z_i = 0, \\ &\qquad \& \ (1)\text{–}(19) \backslash \{(15), (17)\}, \end{aligned} \tag{24}$$

that $i \in \{1, \ldots, N_H\}$ presents each household index in the residential group, $\overline{Z}$ depicts the average of global variables, F_i^{ind} defines the household i's individual objectives, F^{shr} expresses the shared objective in the residential group, and cr denotes the coordination level to determine the importance of shared objectives compared to selfish ones. The cr takes a value between 0 and 1. The $cr = 1$ maximizes the coordination level to use the maximum existing coordination potential in the group. However, the $cr = 0$ represents the selfish case and highlights that there is no coordination among agents. The coordinator chooses the cr value and utilizes the group's flexibility to increase the total gain. The problem (24) can be implemented by a scaled structure of sharing-consensus-based ADMM [16] in a distributed manner based on,

$$u_i^{k+1} := \underset{u_i}{\operatorname{argmin}}\big(F_i^{ind}\left(u_i\right) + \frac{\rho}{2}||u_i - u_i^k + \Delta_i^k||_2^2\big), \tag{25}$$

$$\overline{Z}^{k+1} := \underset{\overline{Z}k}{\operatorname{argmin}}\big(cr\ F^{shr}(N_H \overline{Z}^k) + \frac{N_H\ \rho}{2}||\Psi^{k+1}||_2^2\big), \tag{26}$$

$$\lambda^{k+1} = \lambda^k + \overline{u}^{k+1} - \overline{Z}^{k+1}, \tag{27}$$

where ρ presents the convergence rate, k indexes the iterations, u_i^k symbolizes household i's decision in iteration k, $\overline{Z}^k$ states the average of global variables, and λ^k defines the dual variables. $\Delta_{i,}^k$ is computed by,

$$\Delta_i^k = \overline{u}^k - \overline{Z}^k + \lambda^k, \tag{28}$$

where $\overline{u}^k$ represents the average of all households' decisions in the residential group. Ψ^{k+1} is calculated by,

$$\Psi^{k+1} = \overline{Z}^k - \lambda^k - \overline{u}^{k+1} \tag{29}$$

The procedure performed by (25)–(27) divides shared objectives among HEMS agents in a residential group, makes a consensus between them and satisfies their self-interested objectives. As described in (25), each HEMS agent solves a convex optimization to update its decision in a parallel manner with others. In the next step, the coordinator collects all agents' decisions, calculates their average ($\overline{u}^{k+1}$), and computes $\overline{Z}^{k+1}$ through (26) to satisfy the shared objectives in the group. Afterward, the coordinator updates the dual variables through (27) and returns updated global and dual variables to HEMS agents. The process and the interaction among the coordinator and agents are repeated until they reach a global agreement (known as consensus). The process will be terminated once the agents achieve consensus, which means meeting the predefined stopping criteria or reaching the maximum iteration limit. The stopping criteria include achieving the residual term close to zero ($\lambda^k + \overline{u}^{k+1} - \overline{Z}^{k+1}$) as iterations increase ($k \to \infty$), the agents' objective function approaching the optimal value ($u_i^{k+1} \to u_i^*$), and the dual variable converging to a dual optimal point ($\lambda^{k+1} \to \lambda^*$). Shared objectives are designed to improve the aggregate profile's load factor and minimize the total energy cost in the group. Accordingly, HEMSs individual objectives and groups' shared objectives are defined as,

$$F_i^{ind}\left(u_i\right) = \sum_{h=0}^{H}\left[\pi u_i^T(h) + d_i(h)\right], \tag{30}$$

$$F^{shr}\left(N_H \overline{Z}\right) = \left\| N_H \overline{Z} - \left(\sum_{h=0}^{H} \frac{N_H \overline{Z}_h}{H}\right)\right\|_2^2 + \left\| \sum_{h=0}^{H} N_H \overline{Z}_h \right\|_2^2, \tag{31}$$

that u_i and d_i stand for each HEMS agent's decision (energy profile) and discomfort, respectively.

4.3. Society hierarchical multi-level coordination

This section reformulates the problem (23) as a hierarchical multi-level coordination framework. The hierarchical framework includes lower-level and higher-level coordination. Interactions among the grid coordinator, local coordinators, and household agents are implemented by linking higher and lower levels. The society coordination process is as follows. First, all HEMSs in the residential groups solve their individual optimization problems, make their decisions, and transmit updated decisions to their corresponding local coordinator. Second, the local coordinators collect the HEMSs' decisions and solve their optimization problem to achieve the shared objectives to mitigate the specific challenge in their residential group. Third, this process continues until each local coordinator makes a consensus in its associated residential group. Subsequently, the society coordinator collects local coordinators' decisions, updates the society status (aggregate profile and its load factor), and solves its convex optimization to achieve its shared objectives in order to mitigate the challenges. Afterward, it updates its global variables and dual variables and sends them back to local coordinators. This iterative process continues until the society coordinator makes a global agreement in the community among the local coordinators.

4.3.1. Lower-level coordination

The lower-level coordination among consumers in each residential group is supervised by its corresponding local coordinator and implemented by (32)–(34).

$$u_{i,L}^{k_L+1} := \underset{u_{i,L}}{\operatorname{argmin}}\big(F_{i,L}^{ind}\left(u_{i,L}\right) + \frac{\rho_L}{2}||u_{i,L} - u_{i,L}^{k_L} + \Delta_{i,L}^{k_L}||_2^2\big), \tag{32}$$

$$\overline{Z}_L^{k_L+1} := \underset{\overline{Z}_L k_L}{\operatorname{argmin}}\ \big(\ cr\ F_L^{shr}(N_H \overline{Z}_L^{k_L}) + \frac{N_H\ \rho_L}{2}||\Psi_L^{k_L+1}||_2^2 + \frac{\rho_G}{2}||\Omega_{LG}^{k_L}||_2^2\ \big), \tag{33}$$

$$\lambda_L^{k_L+1} = \lambda_L^{k_L} + \overline{u}_L^{k_L+1} - \overline{Z}_L^{k_L+1}, \tag{34}$$

where k_L depicts the iteration within the lower-level coordination process, L indexes the variables related to local-level (lower-level) coordination, G lists the variables related to grid-level (upper-level) coordination, and LG expresses the variables exchanged between these two levels. N_H denotes the number of houses in each group, ρ_L describes the convergence rate in the lower-level coordination, ρ_G represents the convergence rate in the upper-level coordination, $i \in \{1, \dots, N_H\}$ symbolizes each house index, $u_{i,L}^{k_L}$ designates house i's decision in iteration k_L of the lower-level coordination, $\overline{Z}_L^{k_L}$ defines the average of global variables in iteration k_L within the lower-level coordination, $\lambda_L^{k_L}$ states the dual variables in the lower-level coordination, $F_{i,L}^{ind}$ (defined by (41)) specifies the individual objectives of house i, and F_L^{shr} (formulated by (46)) determines the shared objective of each residential group transmitted by its corresponding local coordinator. $\Delta_{i,L}^{k_L}$ is computed through,

$$\Delta_{i,L}^{k_L} = \overline{u}_L^{k_L} - \overline{Z}_L^{k_L} + \lambda_L^{k_L}, \tag{35}$$

where $\overline{u}_L^{k_L}$ typifies the average of all houses' decisions in the same group. $\Psi_L^{k_L+1}$ is calculated by,

$$\Psi_L^{k_L+1} = \overline{Z}_L^{k_L} - \lambda_L^{k_L} - \overline{u}_L^{k_L+1} \tag{36}$$

Besides, $\Omega_{LG}^{k_L}$ refers to,

$$\Omega_{LG}^{k_L} = N_H \overline{Z}_L^{k_L} - N_H \overline{u}_L^{k_L} + \Delta_{j,G}^{k_G}, \tag{37}$$

that $j \in \{1, \dots, N_{CR}\}$ signifies each local coordinator index and N_{CR} denotes the number of local coordinators in the society. In the suggested architecture, $\Omega_{LG}^{k_L}$ links the upper-level (grid) and the lower-level (local) coordination processes considering $\Delta_{j,G}^{k_G}$. $\Delta_{j,G}^{k_G}$ can be expressed through,

$$\Delta_{j,G}^{k_G} = \overline{u}_G^{k_G} - \overline{Z}_G^{k_G} + \lambda_G^{k_G}, \tag{38}$$

where in the upper-level coordination, $\overline{u}_{G}^{k_G}$ states the average of all local coordinators' decisions in iteration k_G, $\overline{Z}_{G}^{k_G}$ denotes the average of global variables, and $\lambda_{G}^{k_G}$ typifies the dual variables. Moreover, $\overline{Z}_{L}^{k_L}$, $\overline{Z}_{G}^{k_G}$, $\overline{u}_{L}^{k_L}$, and $\overline{u}_{G}^{k_G}$ are calculated based on,

$$\overline{Z}_{L}^{k_L} = \frac{\sum_{i=1}^{N_H} Z_{i,L}^{k_L}}{N_H}, \quad \overline{Z}_{G}^{k_G} = \frac{\sum_{j=1}^{N_{CR}} Z_{j,G}^{k_G}}{N_{CR}} \tag{39}$$

$$\overline{u}_{L}^{k_L} = \frac{\sum_{i=1}^{N_H} u_{i,L}^{k_L}}{N_H}, \quad \overline{u}_{G}^{k_G} = \frac{\sum_{j=1}^{N_{CR}} u_{j,G}^{k_G}}{N_{CR}} \tag{40}$$

that $Z_{i,L}^{k_L}$ represents the global variable of the lower-level coordination related to house i in the iteration k_L, $Z_{j,G}^{k_G}$ stands for the global variable of the upper-level coordination related to local coordinator j, $u_{i,L}^{k_L}$ presents the house i's decision within the local coordination in the iteration k_L, and $u_{j,G}^{k_G}$ symbolizes the decision of the local coordinator j. $F_{i,L}^{ind}$ is formulated through,

$$F_{i,L}^{ind}\left(u_{i,L}\right) = \sum_{h=1}^{H} \pi\left(u_{i,L}^{BH} + u_{i,L}^{FL}\right) + \delta_{i,L}\left(T_{i,L}^{\text{comf}} - T_{i,L}^{u_{i,L}}\right)^2, \tag{41}$$

Therefore, the individual objectives of each consumer minimize the electricity bill ($\sum_{h=1}^{H} \pi\left(u_{i,L}^{BH} + u_{i,L}^{FL}\right)$) and maximize the comfort ($\sum_{h=1}^{H} \delta_{i,L}\left(T_{i,L}^{\text{comf}} - T_{i,L}^{u_{i,L}}\right)^2$), where $u_{i,L} = u_{i,L}^{BH} + u_{i,L}^{FL}$ expresses the total energy consumption of ith house, u_i^{BH} explains BH's energy consumption, $u_{i,L}^{FL}$ defines fixed (non-schedulable) load, $T_{i,L}^{\text{comf}}$ represents the desired (best comfort) indoor temperature, $\delta_{i,L}$ stands for the comfort levels across all time-slots. Consumers select the comfort levels from the possible value set $\delta_{set} = \{\delta_{\min}, \delta_{\max}\}$. $\delta_{i,L} = \delta_{\max}$ means the residents are interested in comfort mode. The suggested process for operation mode selection maximizes consumer flexibility with respect to thermal constraints. This procedure sets the comfort ($\delta_{i,L} = \delta_{\max}$) or economic ($\delta_{i,L} = \delta_{\min}$) modes within all time slots. Consequently, the HEMS agent modifies the BH energy consumption profile to adjust the indoor temperature regarding the following constraints,

$$T_{i,L}^{u_{i,L}} \in [T_{i,L}^{\min}, T_{i,L}^{\max}], \tag{42}$$

$$\delta_{set} = \{\delta_{\min}, \delta_{\max}\}, \tag{43}$$

$$u_{i,L}^{BH} \in [u_{i,L}^{BH,\min}, u_{i,L}^{BH,\max}], \tag{44}$$

$$u_{i,L} \in [u_{i,L}^{\min}, u_{i,L}^{\max}], \tag{45}$$

where $T_{i,L}^{\min}$ and $T_{i,L}^{\max}$ define the minimum and maximum acceptable indoor temperatures, respectively, $u_{i,L}^{BH,\min}$ and $u_{i,L}^{BH,\max}$ determine BH's nominal minimum and maximum energy usages, respectively, and $u_{i,L}^{\min}$ and $u_{i,L}^{\max}$ symbolize household minimum and maximum acceptable energy demands, respectively. The consumer's flexibility level (ability to participate in a DR program) is modeled by setting $\delta_{i,L}$ and $T_{i,L}^{\text{comf}}$ during the day. F_{L}^{shr} is formulated based on,

$$F_{L}^{shr}\left(N_H \overline{Z}_{L}^{k_L}\right) = \left\| N_H \overline{Z}_{L}^{k_L} - \left(\sum_{h=0}^{H} \frac{N_H \overline{Z}_{L}^{k_L,h}}{H} \right) \right\|_2^2 + \left\| \sum_{h=0}^{H} N_H \overline{Z}_{L}^{k_L,h} \right\|_2^2, \tag{46}$$

Therefore, the shared objectives of each local coordinator look for flattening the aggregate profile of the corresponding residential group and minimizing the aggregate electricity bill. The stoppage criteria for reaching local consensus in each residential group is when the agents achieve a close-to-zero residual term as iterations increase, their objective functions approach optimal values, and their dual variables converge to dual optimal points.

4.3.2. Upper-level coordination

The upper-level coordination among local coordinators under the supervision of the grid coordinator can be described by (47)–(50).

$$u_{j,G}^{k_G} = \sum_{i=0}^{N_H} u_{i,L}^{k_L+1}, \tag{47}$$

$$u_{j,G}^{k_G+1} := \underset{u_{j,G}}{\text{argmin}}\left(F_{j,G}^{ind}\left(u_{j,G}\right) + \frac{\rho_G}{2}||u_{j,G} - u_{j,G}^{k_G} + \Delta_{j,G}^{k_G}||_2^2\right), \tag{48}$$

$$\overline{Z}_{G}^{k_G+1} := \underset{\overline{Z}_{G}^{k_G}}{\text{argmin}}\left(cr\ F_{G}^{shr}(N_{CR}\ \overline{Z}_{G}^{k_G}) + \frac{N_{CR}\ \rho_G}{2}||\Psi_{G}^{k_G+1}||_2^2\right), \tag{49}$$

$$\lambda_{G}^{k_G+1} := \lambda_{G}^{k_G} + \overline{u}_{G}^{k_G+1} - \overline{Z}_{G}^{k_G+1}, \tag{50}$$

where N_{CR} determines the number of local coordinators in the society, $j \in \{1, \dots, N_{CR}\}$ shows each local coordinator index, ρ_G symbolizes the convergence rate in the upper-level coordination, $u_{j,G}^{k_G}$ represents local coordinator j's decision in iteration k_G within the upper-level coordination, $\overline{Z}_{G}^{k_G}$ defines the average of global variables within the upper-level coordination, $\lambda_{G}^{k_G}$ designates the dual variables in the upper-level coordination, $F_{j,G}^{ind}$ (depicted in (52)) establishes the individual objectives of local coordinator j, and F_{G}^{shr} (depicted in (53)) specifies the shared objectives of the society transmitted by the grid coordinator to local coordinators. $\Psi_{G}^{k_G+1}$ is defined through,

$$\Psi_{G}^{k_G+1} = \overline{Z}_{G}^{k_G} - \lambda_{G}^{k_G} - \overline{u}_{G}^{k_G+1} \tag{51}$$

Individual objectives of the local coordinator j and shared objectives of the society are described by (52) and (53), respectively.

$$F_{j,G}^{ind}\left(u_{j,G}\right) = \left\| u_{j,G}^{k_G} - \left(\sum_{h=0}^{H} \frac{u_{j,G}^{k_G,h}}{H} \right) \right\|_2^2 + \left\| \sum_{h=0}^{H} u_{j,G}^{k_G,h} \right\|_2^2, \tag{52}$$

$$F_{G}^{shr}\left(N_{CR}\overline{Z}_{G}^{k_G}\right) = \left\| N_{CR}\overline{Z}_{G}^{k_G} - \left(\sum_{h=0}^{H} \frac{N_{CR}\overline{Z}_{G}^{k_G,h}}{H} \right) \right\|_2^2 + \left\| \sum_{h=0}^{H} N_{CR}\overline{Z}_{G}^{k_G,h} \right\|_2^2, \tag{53}$$

Accordingly, local coordinators flatten their corresponding aggregate profile and minimize the aggregate bill. Similarly, the grid coordinator improves the society's load factor and reduce the society's total cost. As mentioned, the players of the hierarchical coordination in the society are the grid coordinator, local coordinators, and households. The players, their tasks, and exchanging data during the proposed procedure have been highlighted in Fig. 2. As illustrated in this Figure, there are two types of consensus in the coordination accounting for the local consensus (agreement) in each residential group and the general consensus in the society. In the former case, each local coordinator updates its group's local agreement in each iteration. However, in the latter case, the grid coordinator updates the society consensus based on updated agreements from the local consensuses of residential groups. Consequently, the iterative hierarchical coordination process reaches a global agreement in society. Indeed, in every iteration, the players update their decisions to fulfill their objectives and exchange data or decisions as shown in Fig. 2. Data exchange in the hierarchical framework builds hierarchical coordination in society and meets individual/shared objectives.

Fig. 2 summarizes the proposed hierarchical coordination process in society. The first step of the coordination process includes initialization, defining the electricity price, and receiving the weather forecast. The initialization specifies the initial values of parameters/variables of the models and the coordination algorithm. It also sets the initial states of players (their decisions). Afterward, HEMSs in every residential group solve their optimization problems to fulfill their corresponding

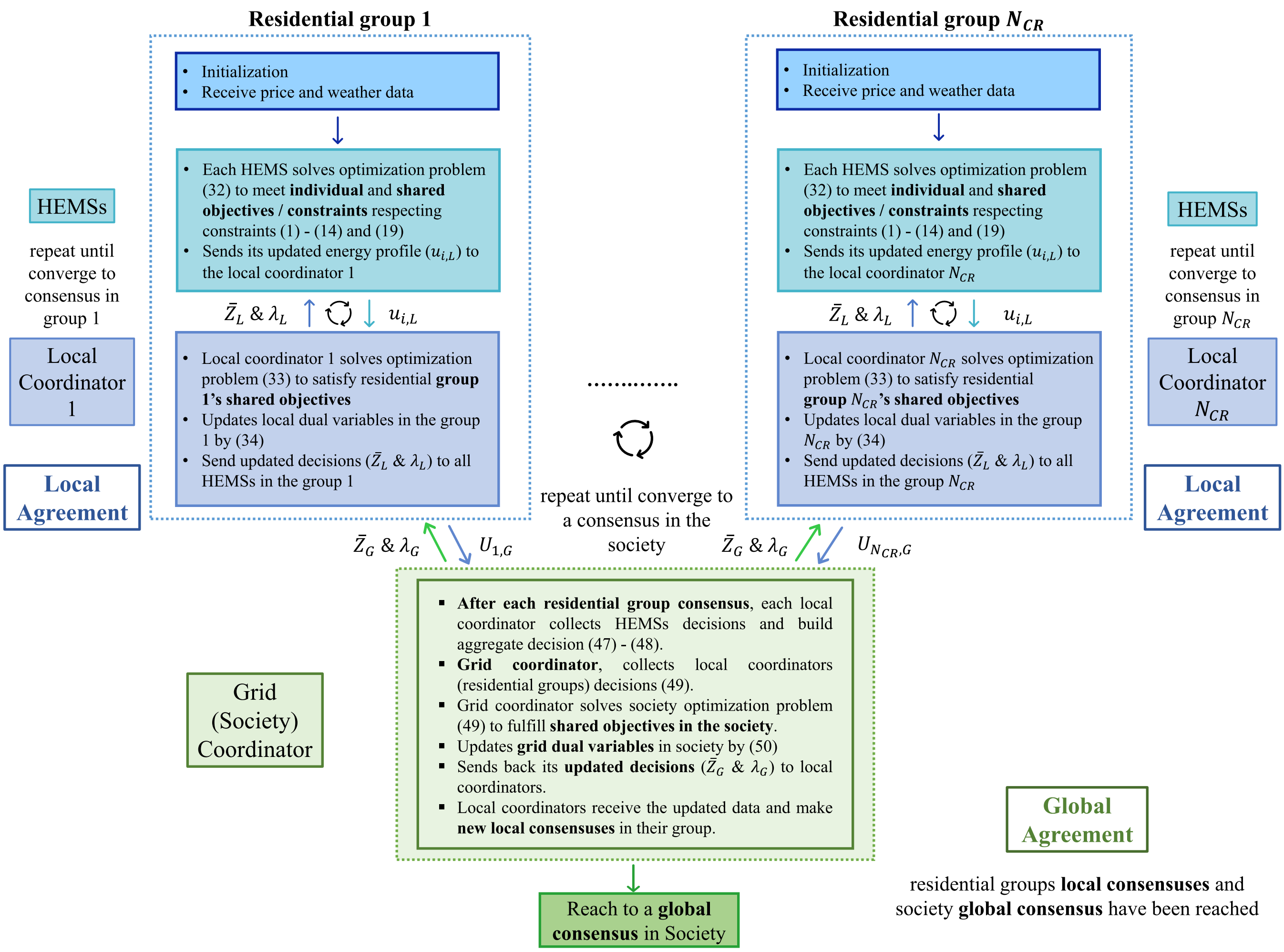


Fig. 2. Proposed hierarchical HEMSs coordination topology, players' tasks, and their interactions.

individual objectives, group-shared goals, and society-shared objectives. Subsequently, each HEMS transmits its updated profile to the affiliated local coordinator. After collecting all household decisions by the corresponding local coordinator, each local coordinator solves its optimization problem to satisfy both group's and society's shared objectives. Afterward, local coordinators send their updated decisions to the grid coordinator to solve the society optimization problem and the specific challenges at the societal level. The grid coordinator updates its global and dual variables and transmits them to the local coordinator. The local coordinators update their global/dual variables and send them to all houses in the corresponding group. As a result, each HEMS tries to solve its problem according to the updated global/dual variables. This procedure constitutes one iteration of the iterative hierarchical coordination system and continues until the local and grid coordinators reach a global consensus at the societal level and the optimization problem converges into the solution.

The operation of the proposed hierarchical HEMSs coordination algorithm and each player's objectives has been summarized in Fig. 3.

5. Coupled constraints distribution mechanism

This section presents a mechanism to distribute the coupled constraints of the society and residential groups among the consumers. The coupled constraints-sharing mechanism leads to the consideration of the constraints in each consumer's decision-making process. The coupled constraints are reformed based on their equivalent formula as (54)–(55), respectively [43].

$$\max\left\{\sum_{j=1}^{N_{CR}}\sum_{i=1}^{N_H} u_{ji}^T(h),\ U_{max}^S\right\}^2, \tag{54}$$

$$\max\left\{\sum_{i=1}^{N_H} u_{ji}^T(h),\ U_{max}^{RG_j}\right\}^2, \tag{55}$$

Afterward, we employ a relaxation [43,44] to transfer the coupled constraints as the shared objectives through the proposed hierarchical coordination procedure. Accordingly, each local coordinator and each consumer consider these constraints in their decision-making process. This leads to the reformulation of the local coordinators' and society's shared objectives, (46) and (53), as (56) and (57), respectively, in order to share the coupled constraints among the players.

$$\begin{aligned} F_L^{shr}\left(N_H \bar{Z}_L^{k_L}\right) &= \left\| N_H \bar{Z}_L^{k_L} - \left(\sum_{h=0}^{H} \frac{N_H \bar{Z}_L^{k_L,h}}{H}\right)\right\|_2^2 \\ &+ \left\|\sum_{h=0}^{H} N_H \bar{Z}_L^{k_L,h}\right\|_2^2 + \Gamma_L^{const}\left\|\max\left\{U_{max}^{RG_j},\ N_H \bar{Z}_L^{k_L,h}\right\}^2\right\|_2^2, \end{aligned} \tag{56}$$

$$\begin{aligned} F_G^{shr}\left(N_{CR} \bar{Z}_G^{k_G}\right) &= \left\| N_{CR} \bar{Z}_G^{k_G} - \left(\sum_{h=0}^{H} \frac{N_{CR} \bar{Z}_G^{k_G,h}}{H}\right)\right\|_2^2 \\ &+ \left\|\sum_{h=0}^{H} N_{CR} \bar{Z}_G^{k_G,h}\right\|_2^2 + \Gamma_G^{const}\left\|\max\left\{U_{max}^{S},\ N_{CR} \bar{Z}_G^{k_G,h}\right\}^2\right\|_2^2, \end{aligned} \tag{57}$$

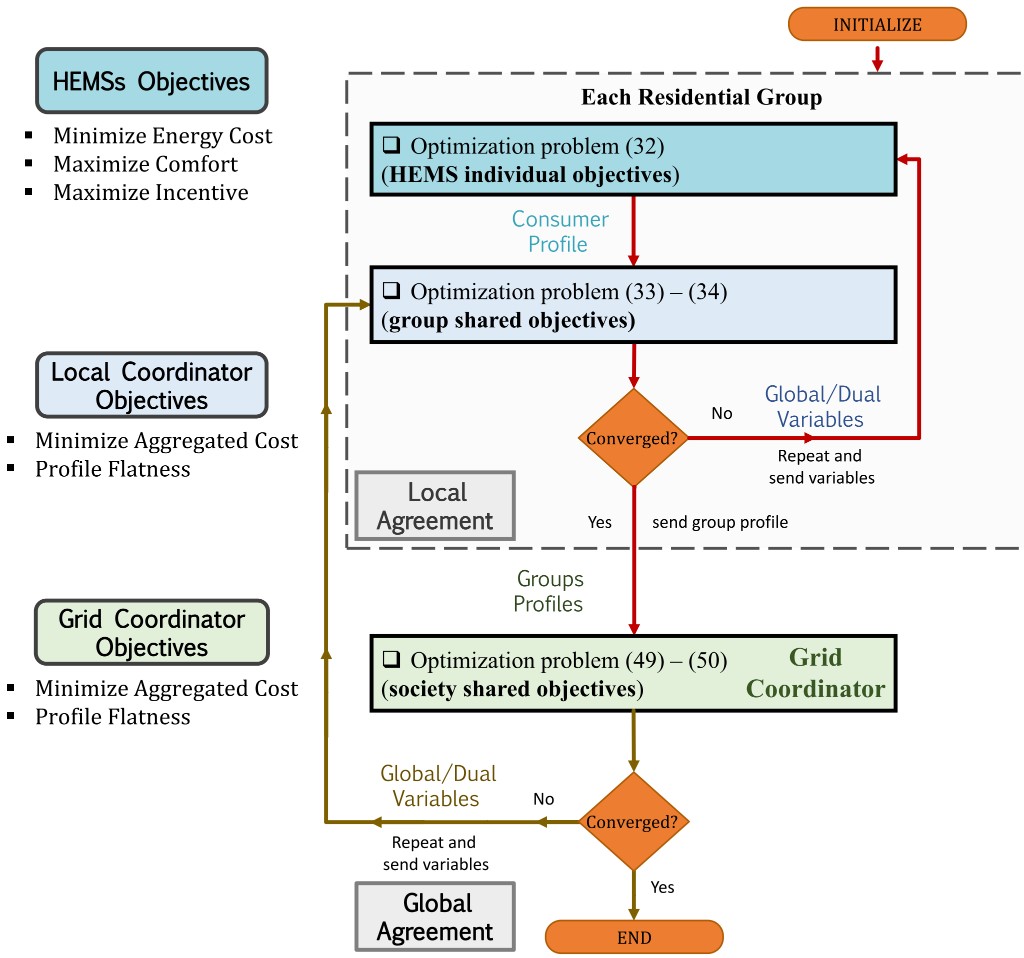


Fig. 3. Proposed hierarchical HEMSs coordination procedure.

where Γ_L^{const} and Γ_G^{const} represent the priority of the shared coupled constraints against the shared objectives. In this work, we consider $\Gamma_L^{const} = \Gamma_G^{const} = 50$ to model a high priority for the coupled constraints. The shared coupled constraints have the highest priority compared to the other shared objectives because of $\Gamma_L^{const}, \Gamma_G^{const}$, and squared maximum operator ($\max\{,\}^2$).

6. Gain distribution mechanism

In the proposed hierarchical HEMSs coordination, households and local coordinators (residential groups) contribute depending on their flexibility and, thus, have different levels of contribution to the coordination. Therefore, it is imperative to measure each household's and group's contribution to distribute the society's total gain among groups and, consequently, allocate each household's share considering its corresponding group's gain. Thereafter, the society's total gain can be allocated between groups, and each group's gain among its households.

In this work, two reward-sharing mechanisms have been devised based on the Shapley values concept to distribute the gain first among the groups and after between the households in each group [45] . The upper-level (society) coalitional game possesses N_{CR} players (local coordinators) and a value (characteristic) function v_G that evaluates each coalition's value and maps players' subsets to the real numbers. Likewise, each lower-level (group) coalitional game has N_H players (consumers) and the characteristic function v_L. The amount that the player (local coordinator) i receives in the given coalitional game $(v_G, \mathbb{C}_G)$ is calculated by (58). The amount that the player (consumer) i obtains in the given coalitional game $(v_L, \mathbb{C}_L)$ is computed by (59).

$$\varphi_i^G(v_G) = \sum_{C_G \subseteq \mathbb{C}_G \setminus \{i\}} \left(\frac{|C_G|!(N_{CR} - |C_G| - 1)!}{N_{CR}!} (v_G(C_G \cup \{i\}) - v_G(C_G)) \right), \tag{58}$$

$$\varphi_j^L(v_L) = \sum_{C_L \subseteq \mathbb{C}_L \setminus \{j\}} \left(\frac{|C_L|!(N_H - |C_L| - 1)!}{N_H!} (v_L(C_L \cup \{j\}) - v_L(C_L)) \right), \tag{59}$$

where the function $v_G : 2^N_{CR} \to R$ presents characteristic functions in the upper-level coalitional game, the function $v_L : 2^N_H \to R$ represents characteristic functions in the lower-level coalitional games, $\mathbb{C}_G$ denotes the set of all players' possible coalitions in the upper-level, $\mathbb{C}_L$ states the set of all players' possible coalitions in each residential group (lower-level games), C_G describes the subsets of all players coalitions existing in the upper-level game, C_L symbolizes the subsets of players coalitions existing in the Lower-level game, $|C_G|$ indicates the cardinality of the subset C_G, $|C_L|$ designates the cardinality of the subset C_L, $v_G(C_G)$ demonstrates the valuation of coalition C_G, $v_L(C_L)$ stands for the worth of coalition C_L, $C_G \subseteq \mathbb{C}_G \setminus \{i\}$ extends the sum over all upper-level game's coalition subsets C_G of $\mathbb{C}_G$ not containing player i, and $C_L \subseteq \mathbb{C}_L \setminus \{i\}$ expands the sum over all lower-level games' coalition subsets C_L of $\mathbb{C}_L$ not containing player i. The function $v_G(C_G)$ signifies that in the given coalition C_G of upper-level game, the total expected payoffs are $v_G(C_G)$ and the function $v_L(C_L)$ indicates that in the given coalition C_L of lower-level games, the total expected payoffs is $v_L(C_L)$. The reward-sharing process in the upper-level game is interpreted as follows. First, each player (local coordinator) creates all the conceivable coalitions with other players. Afterward, the player's marginal contribution $v_G\left(C_G \cup \{i\}\right) - v_G\left(C_G\right)$ as fair equilibrium is computed. Finally, each player's average contribution is calculated over the feasible coalition's permutations. The average contribution of each player can be equivalently reformulated as (60) and (61), for upper-level (local coordinators' shares) and lower-level (consumers' shares) gain distribution, respectively.

$$\varphi_i^G\left(v_G\right) = \frac{1}{N_{CR}} \sum_{C_G \subseteq \mathbb{C}_{\mathbb{G}} \setminus \{i\}} \left(\binom{N_{CR}-1}{|C_G|}^{-1} \left(v_G\left(C_G \cup \{i\}\right) - v_G\left(C_G\right)\right) \right) \tag{60}$$

$$\varphi_j^L\left(v_L\right) = \frac{1}{N_H} \sum_{C_L \subseteq \mathbb{C}_{\mathbb{L}} \setminus \{j\}} \left(\binom{N_H-1}{|C_L|}^{-1} \left(v_L\left(C_L \cup \{j\}\right) - v_L\left(C_L\right)\right) \right) \tag{61}$$

where φ_i^G and φ_j^L symbolize each group's and consumer's shares (in each group), respectively, computed according to their marginal contribution.

The gain-sharing mechanism is budget-balanced, and the summation of all groups' shares is equal to the society's total gain as explained in (62). Besides, the summation of all consumers' shares equals society's total gain.

$$TotalGain = \sum_{i=0}^{N_{CR}} \varphi_i^G = \sum_{i=0}^{N_{CR}} \sum_{j=0}^{N_H} \varphi_{ij}^L \tag{62}$$

The characteristic functions v_G and v_L quantify values of coalitions C_G and C_L through (63) and (64), respectively.

$$v_G\left(C_G\right) = \frac{\left\| U_G^{CR} - U_G^{NCR} \right\|_2^2}{\left\| U_{G,C_N}^{CR} - U_{G,C_N}^{NCR} \right\|_2^2}, \tag{63}$$

$$v_L\left(C_L\right) = \frac{\left\| U_L^{CR} - U_L^{NCR} \right\|_2^2}{\left\| U_{L,C_N}^{CR} - U_{L,C_N}^{NCR} \right\|_2^2}, \tag{64}$$

U_G^{CR} states the aggregate profile of a coalition in the upper level after applying the coordination, U_G^{NCR} denotes the aggregate profile of a coalition in the upper level before the coordination, U_{G,C_N}^{CR} stands for an upper-level grand coalition's profile after the coordination, and U_{G,C_N}^{NCR} expresses an upper-level grand coalition's profile before the coordination. U_L^{CR} presents a lower-level coalition's profile after coordination, U_L^{NCR} symbolizes a lower-level coalition's profile before coordination, U_{L,C_N}^{CR} defines a lower-level grand coalition's profile after coordination, and U_{L,C_N}^{NCR} designates a lower-level grand coalition's profile before coordination. The grand coalition in the upper-level game refers to the coalition that includes all groups (local coordinators), and the grand coalition in the lower-level game refers to the coalition that includes all consumers in the given group. The characteristic function value is in the range of $0 \leq v \leq 1$ and each grand coalition value equals 1.

The presented gain-sharing mechanism has efficiency, individual rationality, symmetry, and null player properties.

7. Simulation and performance evaluation

This section examines the performance of the proposed hierarchical coordination approach and summarizes the numerical results. The simulation seeks to investigate the efficiency and performance of the presented coordination approach regarding the households' flexibility, society size, and coordination level. The simulation measures households' and residential groups' efforts in revising their profile and tests the proposed total gain distribution technique. Furthermore, the presented hierarchical coordination has been compared with the well-known approaches.

7.1. Case study

In the simulation, we use two different societies as case studies. The former case study includes a society that possesses 5 residential groups (local coordinators) and 64 houses. The latter case study consists of a society with 2 residential groups (local coordinators) and 25 households. In the former case study, the society has been formed by connecting 5 residential groups which possess 15, 14, 13, 12, and 10 houses. The society in the latter case study has been constructed by merging 2 residential groups with 15 and 10 households. The properties of the houses used in the case study have been succinctly outlined in Table 2. The table offers an overview of key parameters such as location, number of thermostats, occupants, area, and rooms, providing a detailed snapshot of the real data used to model consumers. The households utilize their BHs as flexible and schedulable assets to participate in the hierarchical coordination program. It is assumed that all houses have been equipped with 10 kW electric baseboard heaters. Households' stochastic consumption profiles and their thermal models have been built using experimental data [16,41]. The simulation setup and parameter definitions for the proposed HTCM are detailed in Table 3. This table provides a comprehensive overview of the key parameters and their values used in our simulations, ensuring clarity and reproducibility of the setup. The data presented in Tables 2 and 3 provide valuable insights into the simulation setup and the physical and electrical characteristics of the case study.

7.2. Baseline

The baseline scenario described in the study does not involve dynamic pricing mechanisms or coordinated demand response strategies. Each agent optimizes its electricity costs and fulfills comfort preferences individually under a fixed daily price of 10 ¢/kWh for all time slots, focusing solely on individual objectives without considering shared objectives or coupled constraints. Fig. 4 illustrates the baseline profiles of residential groups in two case studies comprising 5 and 2 groups. The baseline profile represents the case before the coordination, i.e. DR program is applied. Based on the baseline profiles, the aggregate profile of each residential group includes two major peaks in the morning and evening. The case studies have been built for a cold day in the winter. The proposed hierarchical HEMSs coordination aims to fulfill the consumers' objectives, mitigate the society's aggregate profile peaks, and decrease the total energy cost in each residential group and the society.

7.3. Coupled constraints satisfaction

In this work, as explained in Section 5, a mechanism has been presented to distribute the coupled constraints of the society and residential groups among consumers. In this simulation, the society-level and group-level transformers' maximum energy capacity limits are considered as the coupled constraints of the society and each group. A simulation scenario has been designed to highlight the link between the upper level and the lower level in the proposed hierarchical framework and test the performance of the presented hierarchical coordination in satisfying the coupled constraints. The coupled constraints-sharing mechanism links the consumers' and local coordinators' decision-making process with the coupled constraints at the societal level and group levels. In this scenario, it is assumed that there are no other shared objectives in both upper and lower levels (aggregate cost), and only the shared coupled constraints are considered. These assumptions help highlight the constraints' satisfaction at different levels of the hierarchical framework.

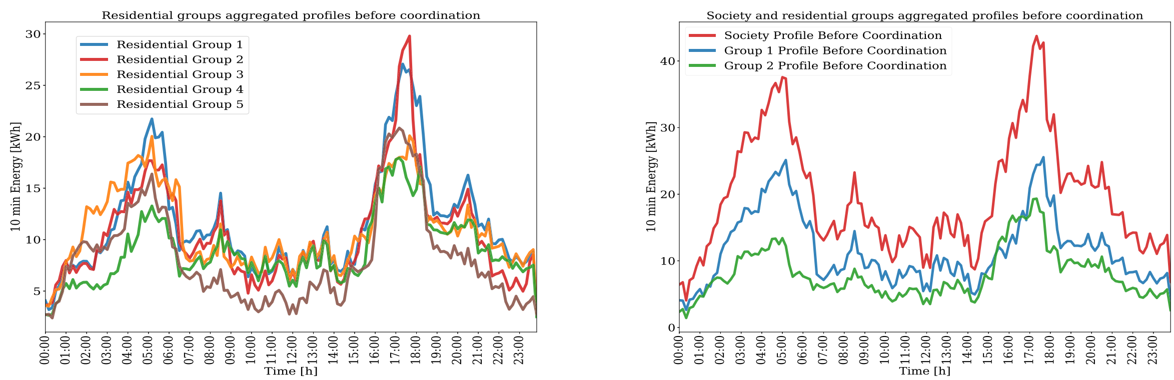
The proposed coupled constraints-sharing mechanism has been tested. This system distributes society's coupled constraints among residential groups' coordinators, and, subsequently distributes the coupled constraints of the residential groups among their corresponding HEMSs. It satisfies the society's and the groups' constraints (maximum

Table 2
Houses characteristics in the case study.

Location	Thermostats number	Occupants	Area (sq. ft.)	Floors number	Basement	Rooms number	Washrooms number	Total rooms	Pool	Pool heater	Spa
Trois-Rivières	8 to 15	1 to 6	1568 to 4020	up to 2	No/Yes	2 to 5	2 to 4	9 to 15	No/Yes	No/Yes	No/Yes

Table 3
Simulation setup and parameter definitions for the proposed HTCM.

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
cr	1	ρ_L	0.065	ρ_G	0.065	H	144 (10 min)	π	$[10...10]_{1\times144}$
$U^{BH,max}$	10 (kW)	$\alpha[min : max]$	[0.9935 0.9998]	β	[0.008 0.299]	γ	[0.00028 0.007]	solver	OSQP(convex)



(a) Society with five groups (b) Society with two groups

Fig. 4. The baseline profiles of residential groups in society.

energy capacities). The society and groups aggregate profiles before and after sharing the coupled constraints without considering other shared objectives have been illustrated in Fig. 5. The results highlight that the coordination meets society's and groups' constraints regarding their corresponding transformers. In the coordination case with the group limit of 25 kWh and society limit of 50 kWh, the coordinators' and consumers' profiles remain almost constant. The profiles do not change significantly because they are already less than the upper limits of the transformers. Therefore, asking the players to modify their profiles is not necessary. In the coordination case with the group limit of 20 kWh and society limit of 40 kWh, each group modifies its profile to fulfill the new boundaries of transformers. In the coordination case with the group limit of 15 kWh and society limit of 30 kWh, profile modifications in residential groups and society are more significant. This case includes more strict coupled constraints and, accordingly, forces players to undergo larger changes compared to other cases. Satisfying the coupled constraints depends on the existing flexibility potentials in the society. If the shared constraints are too strict, consumers can only satisfy them by changing profiles as much as flexibility allows. For example, in the case study, the most strict coupled constraints for group one, group two, and the society are 12.5 kWh, 9 kWh, and 21.5 kWh, respectively.

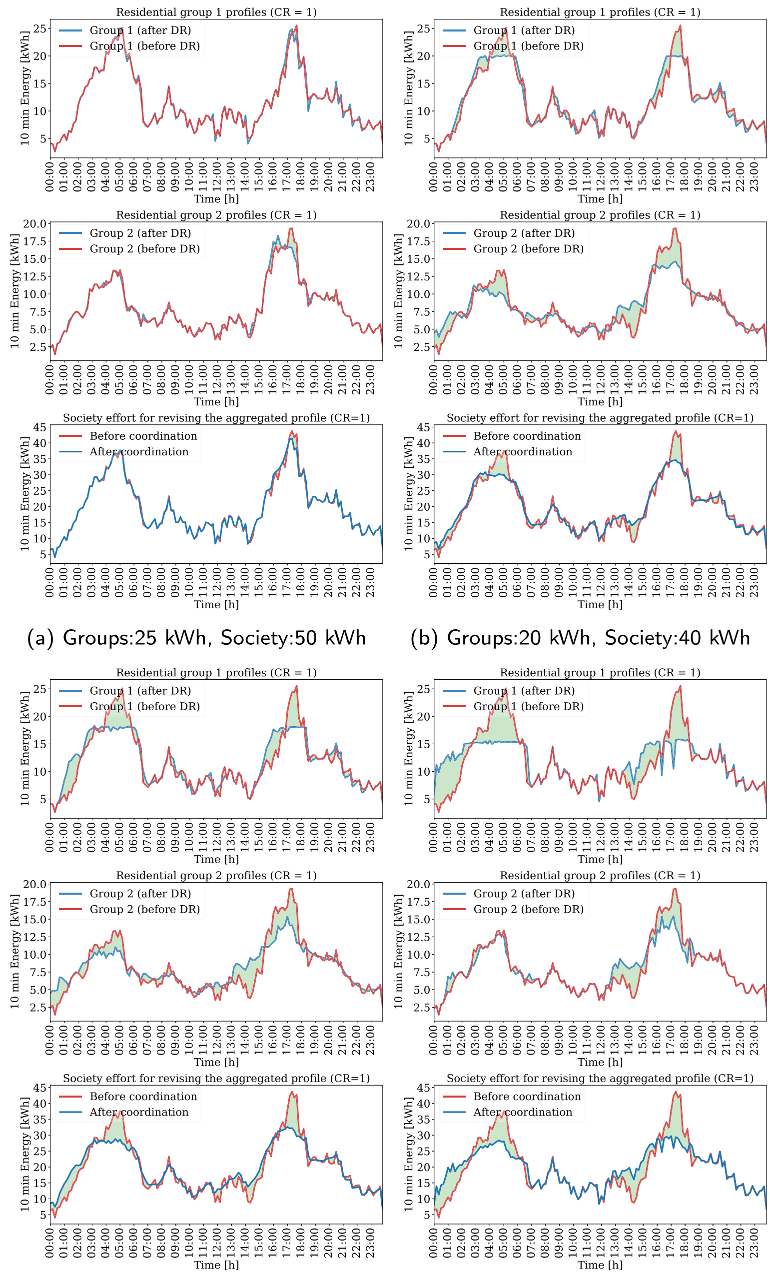
7.4. HTCM scalability

In this section, we demonstrate the scalability and performance of the proposed HTCM, showcasing its functionality with both a larger set of five groups and a focused case with two groups. Fig. 6(a) shows the society aggregate profile before and after applying the proposed approach for the maximum level of coordination ($CR = 1$). In this case study, the society includes five residential groups. This Figure highlights the electricity price and the society's effort in revising its aggregate profile. The coordination decreases the aggregate cost of the baseline case from 120.47$ to 117.88$. Besides, the HEMSs hierarchical coordination improves the society's profile load factor in the baseline case from 0.45 to 0.85. The green area in Fig. 6 highlights the changes in the society's aggregate profile for revising the baseline profile to the coordinated one. The revision includes reducing consumption during the peaks and increasing it during the off-peak periods. The procedure is fair to consumers and residential groups regarding the time by using a fixed price. For example, if the price is not fixed and the coordinator asks a consumer to shift from a low-price period to a high-price period and, then, asks another consumer to shift from a high-price period to a low-price period, the scheduling is not fair. Fig. 6(b) illustrates aggregate profiles before and after applying the developed operation with the maximum level of coordination ($CR = 1$) for a society comprising two residential groups. The society revises its aggregate profile after the coordination to satisfy shared/individual objectives and constraints. The figure presents the society's effort in revising its aggregate profile. In the coordinated case, the society's peak load is decreased significantly.

Fig. 7 shows the residential groups' profiles before and after the practice for the maximum level of coordination ($CR = 1$). This Figure highlights each group's effort in revising its profile. In this case study, the society includes five residential groups. The procedure here does not flatten each group's profile. Instead, it leads the residential groups to execute a complementary action. Therefore, after the coordination, aggregating the groups' profiles makes the society's profile flatten as much as flexibility allows.

Fig. 8 shows residential groups' profiles before and after applying the coordination with the maximum level for a society comprising two residential groups. This Figure highlights each residential group's contribution to the coordination and demonstrates the effort in revising groups' profiles. The effort has been highlighted by green areas, which shows the energy consumption that has been increased or decreased by each group. As illustrated in the Figure, each group, based on the global variables sent by the grid coordinator, shifts and optimizes its consumption specifically during peak period.

Fig. 9 illustrates residential groups' profiles after applying the proposed approach with the maximum level for a society comprising two groups. This Figure highlights the complementary action of residential groups in society. As illustrated, in the time slots that group 1 has higher consumption, group 2 reduces its demand. That is why



(a) Groups:25 kWh, Society:50 kWh

(b) Groups:20 kWh, Society:40 kWh

(c) Groups:18 kWh, Society:36 kWh

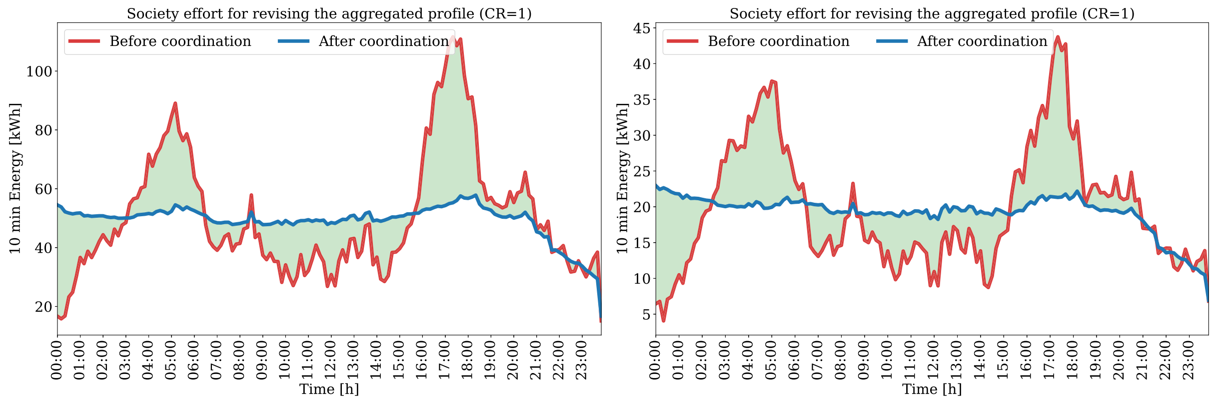
(d) Groups:15 kWh, Society:30 kWh

Fig. 5. The society and groups aggregate profiles before and after applying the coupled constraints of maximum energy capacity in society and residential groups' transformers without considering other shared objectives (aggregated cost minimization and load factor improvement).

in the time slot that one group has a peak (local/global maximum consumption), the other group tries to reach its minimum possible consumption (local/global minimum consumption). Indeed, the grid coordinator leads the local coordinators to distribute their peaks in different time slots during the day and have the minimum overlap between the groups' peak periods. Each local coordinator simultaneously considers its individual objectives/constraints, other residential groups' decisions, and society's shared objectives/constraints. It means each group tries to minimize its cost and improve its load factor. However, for improving society's load factor and minimizing the total cost concurrently, they perform complementary actions. Therefore, the aggregation of groups' profiles flattens the society profile and minimizes the society's total cost. Besides, all of the shared (coupled) and individual constraints in society and groups have been fulfilled during the hierarchical coordination process.

7.5. Comparison: HTCM vs. Alternatives

The HTCM has been compared with the uncoordinated case [46] (selfish optimization with fixed flat price profile), serving as the baseline, along with two other established methods: dynamic price [15,40] and independent coordination [16] approaches. These comparisons aimed to demonstrate HTCM's performance and emphasize its capability to achieve equal or superior outcomes, such as energy efficiency and load factor improvement, compared to other methods. Besides, HTCM shows additional potentials by simultaneously performing well



(a) Society with five groups (b) Society with two groups

Fig. 6. The society aggregated profile before and after applying the proposed hierarchical coordination approach highlighting the price and the society's effort in revising its profile.

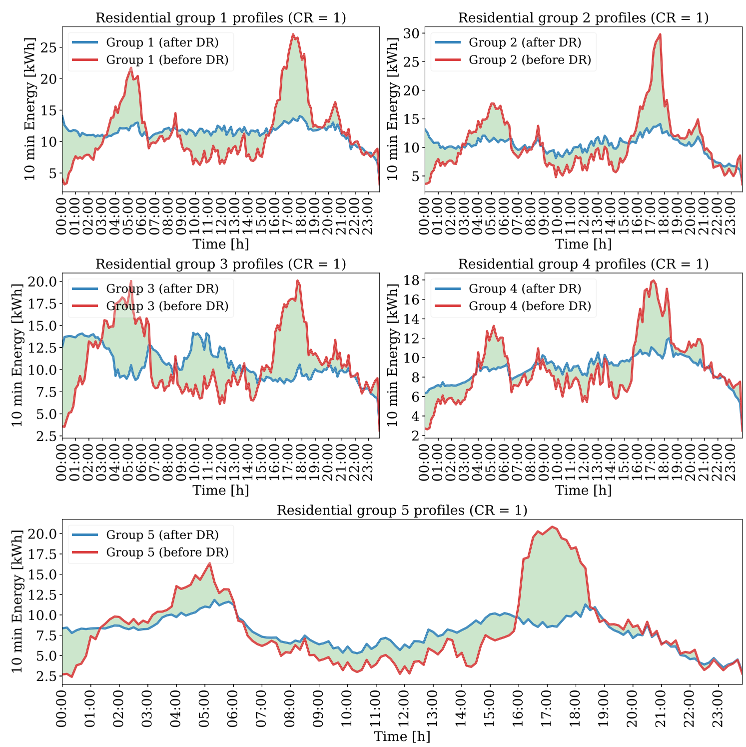


Fig. 7. Residential groups' profiles before and after the hierarchical coordination highlighting each group's effort ($CR = 1$). The society includes five residential groups.

Table 4
A summary of scenarios for comparison of HTCM with well-known methods.

Scenarios (methods)	Price (¢/kWh)	Group shared objectives	Group coupled constraints	Society shared objectives	Society coupled constraints	Number of groups in society
Baseline	$\pi = 10$	✗	✗	✗	✗	✗
Dynamic Price	$\pi = F(U_{Society})$	✗	✗	✓	✓	✗
Independent Coordination	$\pi = 10$	✓	✓	✗	✗	N_{CR}
Proposed HTCM	$\pi = 10$	✓	✓	✓	✓	N_{CR}

and having the ability to address more complex tasks, such as linking decision-making levels and considering coupled constraints across various levels of the distribution system. A summary of scenarios' features for comparison of different well-known methods with the proposed HTCM has been shown in Table 4.

Baseline (before coordination/uncoordinated): The baseline case [46] illustrates a scenario devoid of transactional DR programs or coordination strategies. In this case, each agent conducts individual optimization to minimize electricity costs under a fixed (flat) daily price profile, while also ensuring comfort. The flat price has been set at 10 ¢/kWh

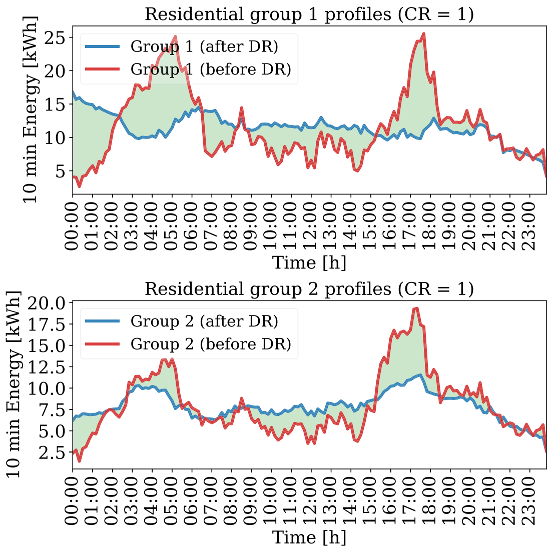


Fig. 8. Residential groups' profiles before and after the hierarchical coordination highlighting each group's effort ($CR = 1$). The society includes two residential groups.

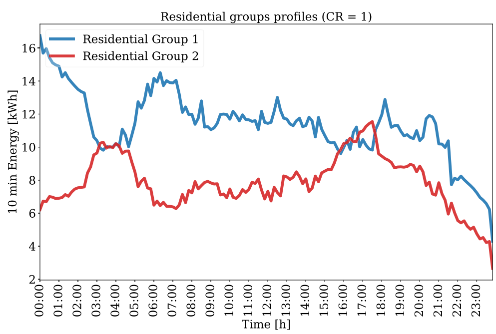


Fig. 9. Residential groups' profiles after the hierarchical coordination highlighting their complementary action. The society includes two residential groups.

according to [42]. Each agent pursues only its individual objectives F^{ind}, as depicted in (30), with $\pi = 10$ ¢/kWh and does not consider any common objectives/constraints.

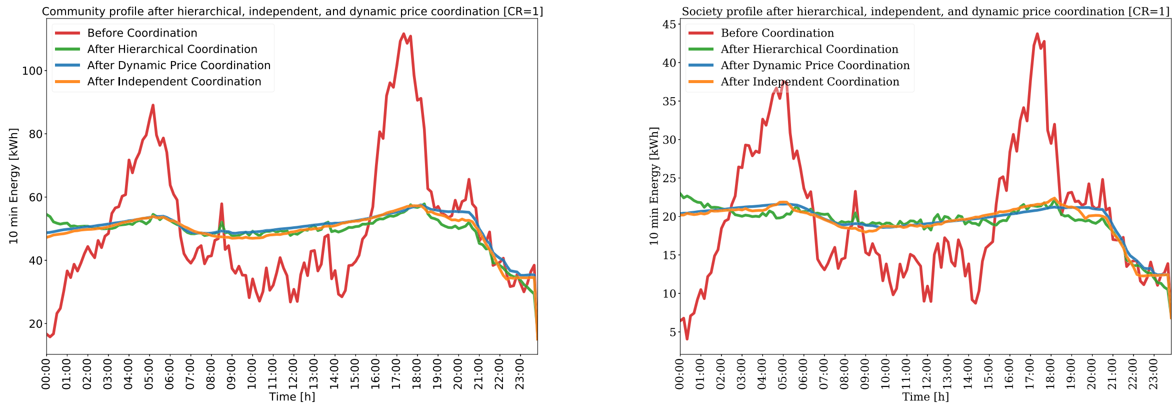
Dynamic price coordination: The dynamic price (negotiated-based pricing) mechanism [15,40] adjusts prices according to the aggregate energy consumption of the entire society, treating all consumers as a single entity without accounting for coupled constraints of different groups or decision-making levels. The dynamic day-ahead price profile is generated at the start of each day through negotiations between consumers and an aggregator within the society. Each agent within the society submits its day-ahead energy demand profile to the aggregator, who aggregates this information to calculate and update the electricity rate. The updated price is then transmitted back to consumers, who adjust again their energy demand profiles accordingly. This iterative process persists until the aggregator has utilized all available flexibility within the society, and the electricity rate profile becomes fixed. The converged price profile will be assigned as the price stabilizes across society. This dynamic pricing model is represented by $\pi^k = 0.52 * U^k_{Society}$, with $U^k_{Society}$ denoting the collective energy profile of the society in iteration k. The variable $U^k_{Society}$ represents the aggregate demand of the society in each iteration, while the coefficient 0.52 denotes the price elasticity used to ensure price fluctuations around the desired value. In this study, the desired value is set at 10 ¢/kWh according to [42]. In this scenario, each agent aims to fulfill its individual objectives F^{ind}, as shown in (30), with $\pi = F(U_{Society})$ ¢/kWh. The dynamic negotiation pricing mechanism by updating parameter π indirectly leads agents towards a common goal. The negotiation-based dynamic price approach, known for leveraging consumer flexibility through demand-based price adjustments, serves as a benchmark for comparing our HTCM, which utilizes flexibility in a distinct manner.

Independent coordination The independent coordination approach [16] scenario involves each residential group coordinating exclusively among its own HEMSs without any communication or coordination with other groups. This coordination framework operates at a single level rather than hierarchically. Each group focuses solely on meeting its own common objectives and addressing its coupled constraints, neglecting the common objectives and coupled constraints of the broader society or other decision-making levels.

Proposed HTCM The proposed HTCM coordination scenario involves two levels of coordination. The primary level ensures coordination among consumers within each residential group, while the subsequent level guarantees coordination among residential groups. This coordination framework operates within a hierarchical structure. Each residential group focuses on meeting its own common objectives and addressing its coupled constraints, while simultaneously fulfilling the common objectives and coupled constraints of the society. The proposed HTCM coordination links the different decision-making levels from the lowest (consumer), through the intermediary (local coordinators), to the highest (grid coordinator).

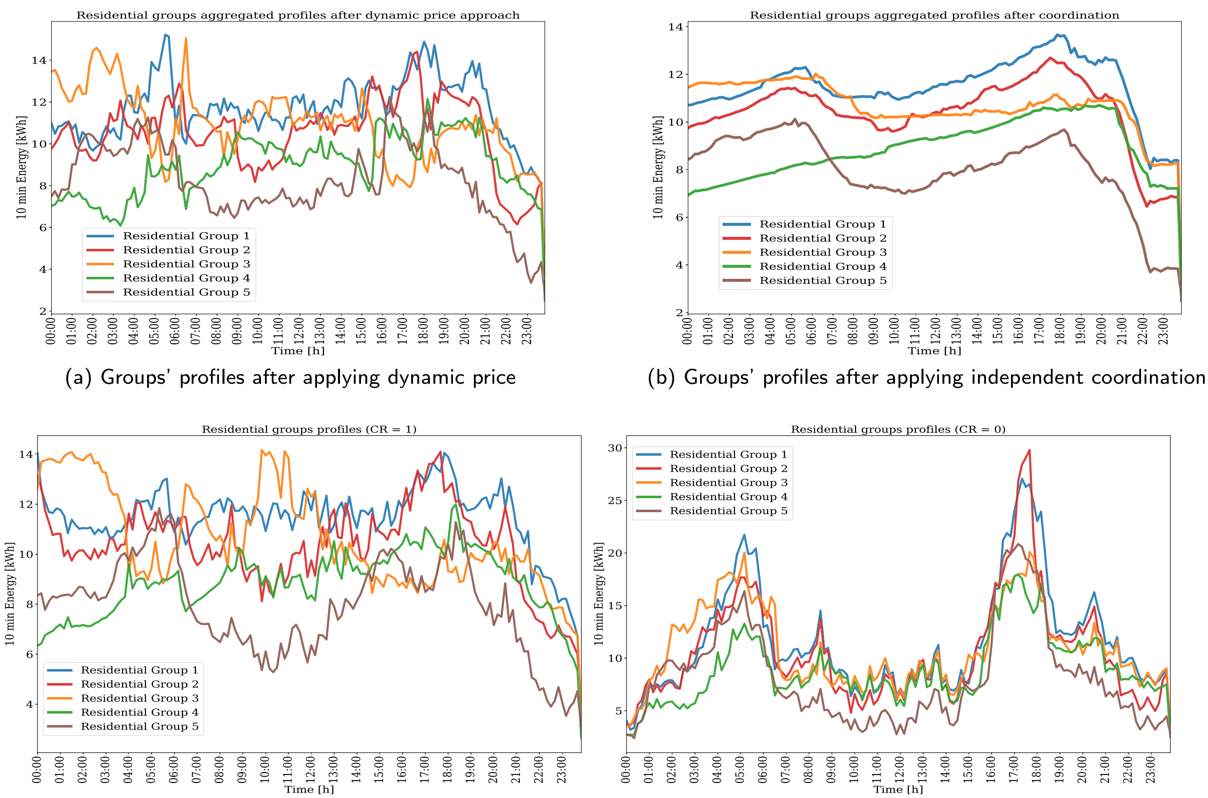
The society's aggregate profiles for baseline, dynamic price, independent coordination, and HTCM cases have been illustrated in Fig. 10. Figs. 10(a) and 10(b) present the aggregate profiles for societies with five and two residential groups, respectively. It can be observed that the HTCM significantly improves society's load factor. The profile flatness has been achieved because of consumers' complementary action and distribution of their peaks during the day through coordinating the HEMSs. The dynamic price method improves the load factor, however, it leads to a higher total cost. Besides, this approach cannot handle the shared objectives and coupled constraints at different levels of society. On the contrary, the proposed mechanism has the capability to improve the load factor with a lower total cost and deal with the shared objectives and constraints in different levels of society. The independent coordination approach also fails to consider society's coupled constraints and make coordination among the residential groups.

In summary, the HTCM creates an opportunity for exploiting consumers' flexibility in order to solve challenges at different levels and meet each level's constraints. This approach can reach the benefits of other well-known methods with a lower energy cost while considering objectives/constraints at different levels. Besides, it is scalable and can be used for a society with different numbers of groups and consumers. As illustrated in Fig. 10, the proposed design performs properly in societies with five and two groups. Table 5 summarizes the comparison of the approaches for a society with five residential groups. The society's aggregate energy cost for baseline, dynamic price, uni-level coordination, and HTCM cases are 120.47, 126.49, 118.39, and 117.88, respectively. Besides, the society's load factor for these methods is 0.45, 0.86, 0.85, and 0.85, respectively. The proposed HTCM not only achieves a 2.1% cost savings compared to without coordination case but also significantly improves the society aggregated profile load factor from 0.45 to 0.85. This dual improvement, alongside the consideration of common objectives and coupled constraints across different levels of the distribution system and linking decision-making levels, highlights HTCM's ability to enhance energy efficiency and system stability through hierarchical coordination. The proposed HTCM's performance emphasizes its capability to achieve equal or superior outcomes compared to other methods, while also excelling in considering multiple tasks, linking decision-making levels (including customers, local coordinators, and the grid coordinator), and addressing common objectives and coupled constraints across all levels. HTCM's multifaceted benefits make it a compelling and practical



(a) Society with five groups (b) Society with two groups

Fig. 10. Comparison of the society's aggregate profiles for baseline, dynamic price, independent coordination, and proposed hierarchical coordination cases.



(a) Groups' profiles after applying dynamic price (b) Groups' profiles after applying independent coordination

(c) Groups' profiles after applying hierarchical coordination (d) Groups' profiles before demand response

Fig. 11. Comparison of groups' profiles for dynamic price, independent coordination, and HTCM cases.

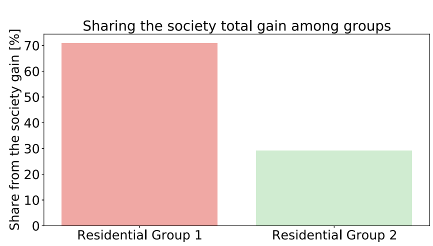


Fig. 12. Each residential group's share from society's total gain.

solution for optimizing energy management in realistic applications. Table 6 summarizes the same for a society with two residential groups. In this scenario, the society's aggregate energy cost for baseline, dynamic price, independent coordination, and HTCM are 49.16, 48.08, 46.22, and 46.12, respectively. Besides, the society's load factor for these schemes is 0.45, 0.87, 0.85, and 0.85, respectively. It can be deduced that the proposed hierarchical approach can effectively optimize the aggregate cost and improve society's load factor.

Fig. 11 presents the results for 5 residential groups' profiles in the society based on the utilized approaches. Fig. 11(a) shows the residential groups' profiles processed by the dynamic price approach. This method reaches a higher energy cost and does not fulfill shared objectives and coupled constraints at different levels of society. The residential groups' profiles after applying the independent coordination

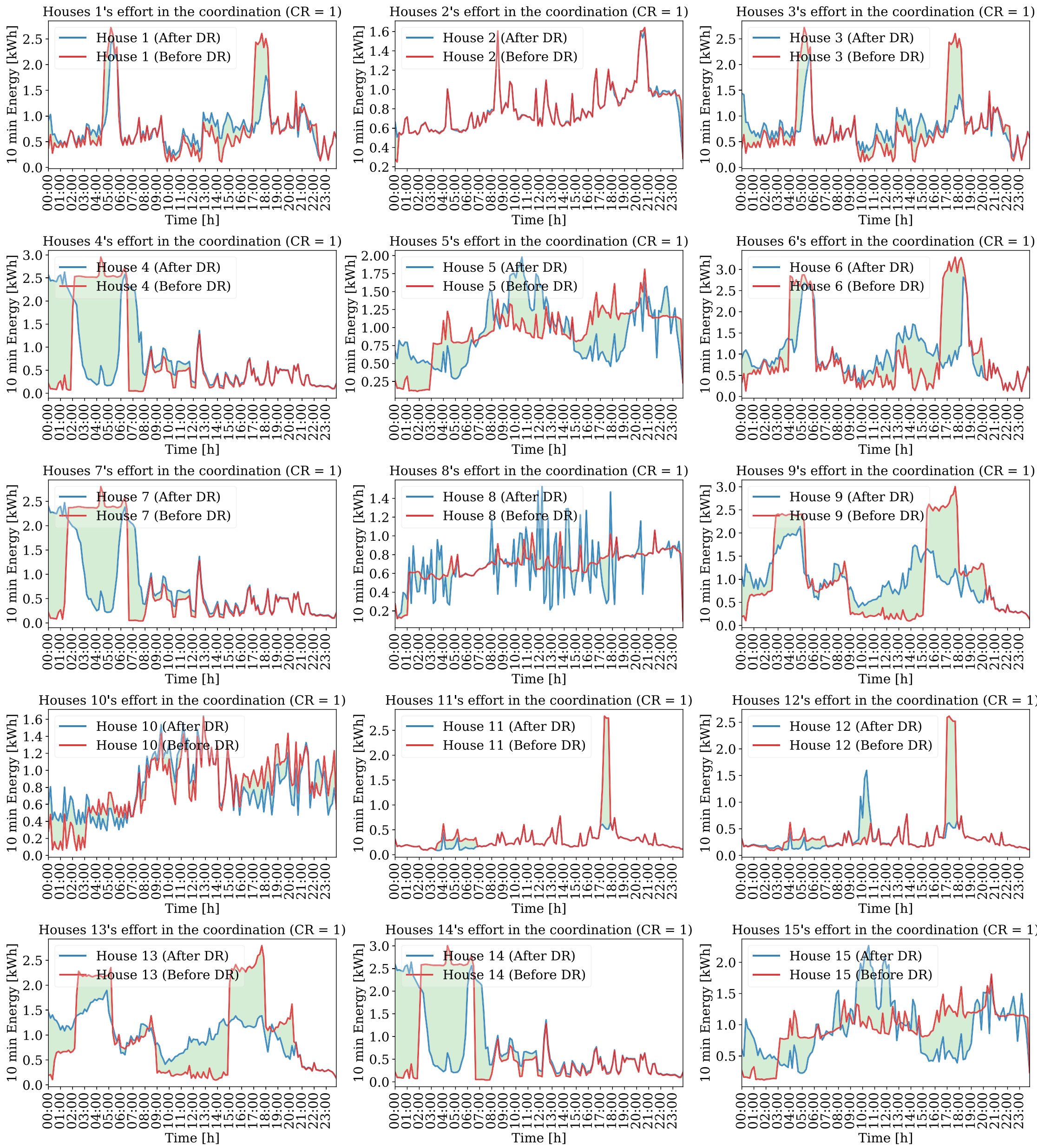


Fig. 13. Each household's effort in the residential group 1.

Table 5
Comparison of the coordination approaches for society with five residential groups.

Society Aggregated Energy Cost [$]			
Proposed Hierarchical Approach	***Independent Coordination***	***Dynamic Price***	***Without Coordination***
117.88	118.39	126.49	120.47
Society Aggregated Profile Load Factor			
Proposed Hierarchical Approach	***Independent Coordination***	***Dynamic Price***	***Without Coordination***
0.85	0.85	0.86	0.45

Table 6
Comparison of the coordination approaches for Society with Two Residential Groups.

Society Aggregated Energy Cost [$]			
Proposed Hierarchical Approach	***Independent Coordination***	***Dynamic Price***	***Without Coordination***
46.12	46.22	48.08	49.16
Society Aggregated Profile Load Factor			
Proposed Hierarchical Approach	***Independent Coordination***	***Dynamic Price***	***Without Coordination***
0.85	0.85	0.87	0.45

method have been shown in Fig. 11(b). This design does not consider coupled constraints and shared objectives in the upper level (society) and does not coordinate the local coordinators. As illustrated in the related Figure, there are no complementary actions among the groups. Fig. 11(c) illustrates the residential groups' profiles after the hierarchical coordination of HEMSs and highlights the complementary action of the residential groups. As shown in this Figure, each group's peak period has been distributed during the day to provide the minimum overlap interval between the groups. Indeed, when one group is in its peak period, the other groups try to decrease their consumption. In the proposed approach, we do not care about the flatness of an individual household profile or each group's profile. In fact, the flatness of the

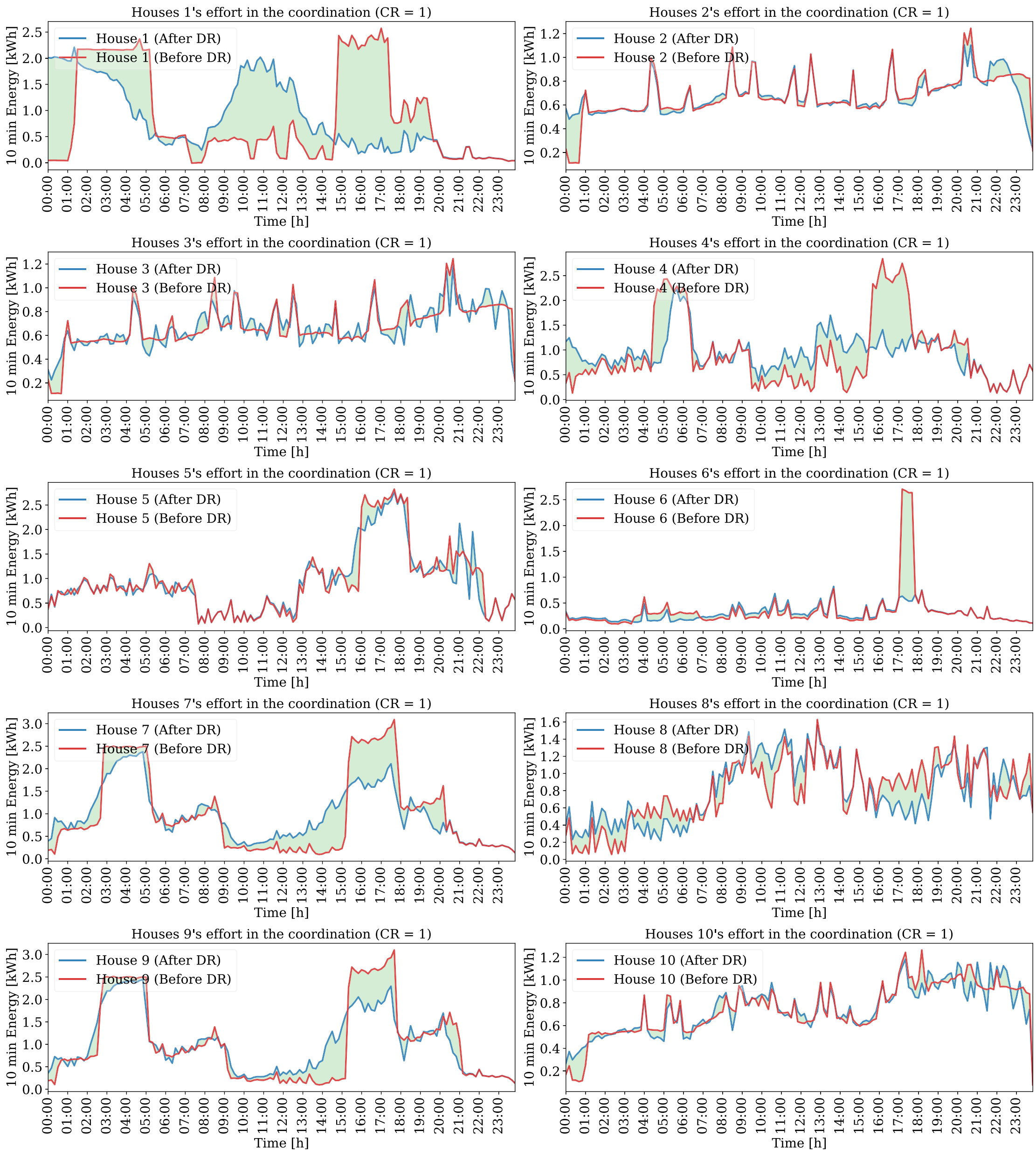


Fig. 14. Each household's effort in the residential group 2.

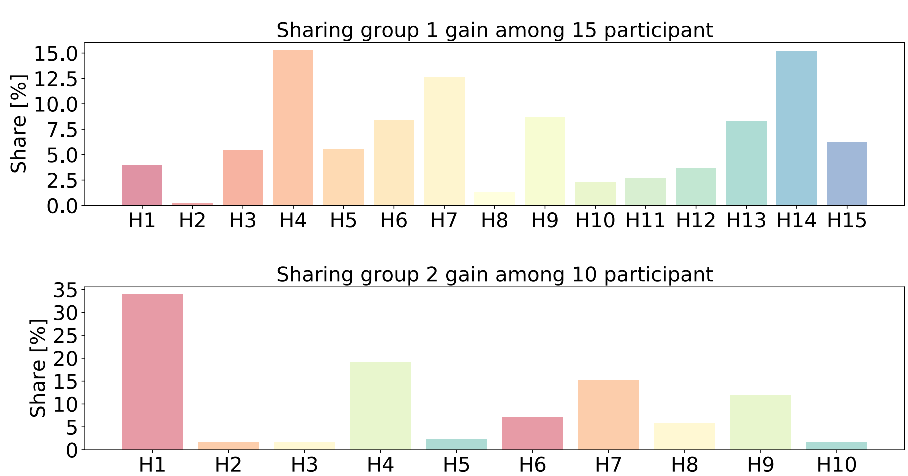


Fig. 15. Each household's share from its associated group's total gain.

society's aggregate load profile is guaranteed by the complementary action of players instead of flattening players' profiles individually. For example, in Fig. 11(c), at time-slot 2, the peak demand of the group 3 is around 14 kWh while the other groups have a lower consumption or reach their local minimum. Indeed, the HTCM tries to optimize consumers', groups', and society's energy consumption profiles, and flatten the groups' and society's profiles by complementary actions of players. The residential groups' profiles before applying the suggested system or any other DR program have been illustrated in Fig. 11(d). In this case, the groups' peaks are almost in the same time slots, which makes a major growth in society's demand. Besides, this case leads to higher consumers', groups', and society's energy costs.

7.6. Contributions and gain sharing

The performance of the proposed total gain-sharing mechanism has been also investigated. This mechanism distributes the total gain of the society among the residential groups according to their contribution to the coordination. Afterward, each group's gain is distributed among consumers based on their effort in revising their profile. The case study for testing the gain-sharing mechanism is a society including two residential groups. It is the same as the one used in Figs. 8 and 9. The society comprises two residential groups in which group 1 possesses 15 houses and group 2 includes 10 dwellings. The marginal contribution of each residential group to the coordination in the society has been calculated by quantifying their effort highlighted in Fig. 8. We have used (58), (60), and (63) to estimate each group's marginal contribution and calculate its share from the society's total gain.

Fig. 12 illustrates each residential group's share after the hierarchical coordination in the society with two groups. Each group's share has been shown by percentage to highlight the differences. As depicted in Fig. 8, the contribution of group 1 is higher compared to group 2. The proposed gain-sharing mechanism allocates almost 70% of the gain to group 1 and 30% of it to group 2. The group 1 earns more share because its normalized marginal contribution is higher than the other group. The sharing mechanism is fair because it is calculated based on players' marginal contributions, and the value of all possible coalitions are measured by their normalized profile revision. Besides, marginal contributions have been computed by averaging all players' viewpoints. Indeed, based on (60), all possible orders (permutations) for engaging a player in the grand coalition have been considered to calculate the marginal contributions. Therefore, the proposed gain-sharing mechanism is fair in calculating and distributing the shares.

After the groups' shares calculation, each group's gain should be distributed among its corresponding consumers. We have employed (59), (61), and (64) to measure and quantify each consumer's marginal contribution and, accordingly, compute each household's share from its corresponding group's gain. First, to distribute each group's gain among its households, it is essential to measure their efforts in coordination. The effort of households in the group 1 and group 2 for revising their profile have been highlighted in Figs. 13 and 14, respectively.

Based on the results, the flexibility levels of households are different. Some consumers have more adjustable preferences, and, thus, are more flexible in contributing to the coordination. For example, houses 4, 5, 6, 7, 9, 13, 14, and 15 from group 1 have higher levels of flexibility than others. In addition, houses 1, 4, 7, and 9 contribute more than other households in group 2. On the contrary, some consumers have strict preferences and, consequently, have lower/no levels of flexibility. For example, house 2 in the group 1 has almost no flexibility and prefers not to contribute to the coordination. Houses 8 and 10 from group 1 as well as houses 3, 5, and 10 from group 2 have a very low contribution to the coordination. Furthermore, some consumers such as houses 1, 3, 11, and 12 from group 1 and houses 2, 6, and 8 from group 1 have low flexibility levels compared to other consumers.

Fig. 15 displays each household's share from its group's gain after the hierarchical coordination. Each consumer's share has been presented by percentage to emphasize the differences. As highlighted in Figs. 13 and 14, consumers' contributions are different that leads to allocating a higher share to the consumer with a higher contribution level. The proposed gain-sharing mechanism allocates higher shares to houses 4 and 14 from group 1 and house 1 from group 2 because they have the highest marginal contribution to the coordination. On the contrary, houses 2, 8, and 10 from group 1 and houses 2, 3, 5, and 10 from group 2 deserve the lowest shares because they are entitled to the lowest marginal contributions. In conclusion, the consumers with higher normalized marginal contribution are identified as significant contributors (highly flexible consumers) and deserve big shares. The marginal contribution has been calculated by (61) to take the average of all marginal contributions derived from the viewpoint of each household.

Furthermore, it is important to acknowledge certain limitations in our study that pave the way for future research avenues. In the gain-sharing mechanism, we utilized the Shapley Value concept within a coalitional game framework involving a set of N players to allocate gains among participants. Our methodology required the formation of all feasible coalitions, with each player computing marginal contributions from their perspective for every possible permutation. This process, while effective in theory, incurs a substantial computational burden, growing exponentially with the number of players (2^N possible coalitions), thus increasing the complexity exponentially as N increases. To address this challenge, future research could explore the development of an estimation function tailored to simplify the computation of the Shapley value, particularly for larger populations of players. Such an approach would not only mitigate computational complexities but also enhance the scalability and applicability in real-world scenarios with extensive participant involvement. Additionally, a communication-related limitation arises from the coordination structure involving multiple residential groups and consumers. Future work could focus on optimizing communication protocols at both upper and lower levels to improve system efficiency and responsiveness.

8. Conclusions

This paper proposed a Hierarchical Transactive Coordination Mechanism (HTCM) to coordinate home energy management systems in a society capable of dealing with consumers' objectives/constraints and local and grid coordinators' shared objectives/coupled constraints under a bottom-up strategy. Specifically, the hierarchical structure distributes the shared objectives of local and grid coordinators to consumers, with the aim of flattening the aggregate consumption profile and reducing the total energy expense at every level. This work developed two additional operations to enhance the proposed coordination scheme. One is a gain-sharing technique that ensures a fair distribution of the total gain obtained by the grid coordinator among the different levels of the hierarchy, starting from the highest level and progressively moving downwards. Additionally, a coupled constraint-sharing method has been devised to establish connections between these levels and adjust consumers' decisions in order to meet the interconnected constraints. The suggested approach has been implemented in a society of agents consisting of HEMS groups that utilize electric baseboard heaters with demand response participation capabilities. The performances of the proposed coordination approach, coupled constraints-sharing mechanism, and gain-sharing mechanism for different case studies have been examined. The HTCM approach has been compared with two other known methods. The results indicated that the proposed HTCM has the capability to enhance the society's aggregate power profile load factor from 0.45 to 0.85. Additionally, it leads to a reduction of the society's total electricity cost by 6.2%. Compared to independent coordination and dynamic price approaches, the HTCM guarantees almost similar or better results in improving the load factor and decreasing the aggregated cost while respecting and distributing the coupled constraints in society and groups.

CRediT authorship contribution statement

Farshad Etedadi: Conceptualization of this study, Methodology, Software, Writing – original draft, Visualization. **Sousso Kelouwani:** Supervision, Reviewing and editing, Project administration. **Kodjo Agbossou:** Supervision, Funding acquisition, Reviewing and editing, Project administration. **Nilson Henao:** Data curation, Supervision, Reviewing and editing. **François Laurencelle:** Supervision, Reviewing and editing. **Sayed Saeed Hosseini:** Supervision, Reviewing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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