

CHALLENGES OF RENEWABLE ENERGY DISTRIBUTION IN MULTI-APARTMENT RESIDENTIAL BUILDINGS: EVIDENCE FROM ARMENIA (2015–2024)

Sergey Minasyan, Mariam Arakelyan*, Ashot Bagdasaryan

National University of Architecture and Construction of Armenia, Yerevan, RA

*mariamaraqelyan@nuaca.am

The study investigates deployment and distributional challenges of renewable energy sources (RES) in multi-apartment residential buildings in the Republic of Armenia. Drawing on longitudinal data from 87 buildings across Yerevan, Gyumri, and Vanadzor (2015–2024), the study quantifies the gap between actual and potential RES adoption, measures distributional inequality using the Gini coefficient, identifies key adoption barriers through a mixed-methods survey instrument, and models predictors of distribution efficiency through Ordinary Least Squares (OLS) regression and K-Means cluster analysis. Results show that the actual RES adoption rate stands at $34,2\% \pm 6,8\%$ against a technical potential of 78...85 %. The Gini coefficient ($G = 0,47$, $SD = 0,12$) reveals substantial distributional inequality. The regression model ($R^2 = 0,61$, $F(6,80) = 20,9$, $p < 0,001$) identifies automated control systems ($\beta = +0,312$, $p < 0,001$), resident awareness ($\beta = +0,224$, $p < 0,01$), and household count ($\beta = -0,178$, $p < 0,01$) as the dominant factors. Policy implications and a 2025–2027 Smart Building pilot are discussed.

Keywords: renewable energy, multi-apartment building, Gini coefficient, energy distribution, OLS regression, smart building, Armenia

Introduction

The global urgency of decarbonising the built environment has placed residential energy systems at the centre of climate policy. In Armenia, the “Green Growth 2030” strategy mandates a 35 % renewable share in the national energy mix by 2030 and 80 % by 2050 [1]. Despite photovoltaic (PV) module costs falling by more than 90 % between 2010 and 2024 [2], multi-apartment buildings remain the least-penetrated housing segment for RES.

The structural barriers are well-documented in international literature [3–5]: fragmented co-ownership, collective-action failures, metering complexity, and low tenant awareness. In the Armenian context, these barriers are compounded by an ageing housing stock (over 60 % of Yerevan’s apartment buildings pre-date 1990), weak homeowners’ association (HOA) governance, and limited access to green finance [6].

Yet empirical evidence on the magnitude and drivers of distributional inequality within these buildings is scarce, particularly in post-Soviet transition economies [7]. This study addresses that gap by combining administrative energy records, resident surveys, and statistical modelling to produce actionable estimates. The research questions are:

- what is the actual versus potential RES adoption rate, and how has it evolved since 2015?
- how unequally is RES-generated electricity distributed across households within a building?
- which building-level and socio-economic factors best predict distributional efficiency?

Materials and Methods

Study Sample and Data Sources .The sample comprises 87 multi-apartment buildings drawn from three cities: Yerevan ($n = 52,0$; 59,8 %), Gyumri ($n = 21,0$; 24,1 %), and Vanadzor ($n = 14,0$; 16,1 %). Buildings were selected via stratified random sampling from the national housing-stock registry, stratified by city, decade of construction (pre-1990 / 1990–2005 / post-2005), and number of storeys. Inclusion criteria required: a minimum of 12 residential units; registration in the State Housing and Communal Services database; presence of at least one PV array or independent generation unit; and complete metered consumption records for the full study period [8].

Three primary data sources were used: (1) metered electricity generation and consumption records obtained from the distribution system operator ELECTRIC NETWORKS OF ARMENIA (2015–2024) [9]; (2) building technical passports from the Ministry of Territorial Administration; and (3) a structured questionnaire administered to 563 residents across the 87 buildings (response rate: 87 %), using a five-point Likert scale to measure awareness, willingness to pay, and perceived fairness (table 1).

Key Variables and Measures

Table 1

Key barriers to RES distribution: building-level and resident-level perspectives

Barrier	Buildings citing (%)	Residents agreeing (%)	Significance
Automated control system unavailable	78,2	67,4	$p < 0,001$
Lack of HOA consensus	54,0	71,2	
Inequitable electricity metering	89,7	55,8	
Technical obsolescence of infrastructure	66,7	48,3	
Financial access constraints	41,4	83,1	

Distributional inequality was operationalised via the Gini coefficient (G), computed from household-level annual RES-energy receipts normalised by floor area [10]. $G = 0$ denotes perfectly equal distribution; $G = 1$ indicates complete concentration. Awareness was measured as the mean Likert score (1...5) across four knowledge items concerning RES technology, tariff structure, HOA rights, and subsidy eligibility.

Analytical Framework

Three complementary analytical methods were applied. First, descriptive statistics and a Lorenz-curve decomposition provided a baseline portrait of adoption and inequality across the sample. Second, K-Means cluster analysis ($k = 3$, determined via the elbow criterion and silhouette scores) grouped buildings into homogeneous typologies [11]. Third, OLS regression modelled G as a function of six independent variables: automated control system presence (D_1 , binary); building construction year (X_2 , continuous); pre-2000 construction dummy (D_3); share of economically active residents (X_4); resident awareness score (X_5); and receipt of state or bank subsidy (X_6 , binary). Heteroscedasticity was corrected using HC3 robust standard errors (table 2).

Table 2

OLS Regression Results — Dependent Variable: Gini Coefficient (G)

Variable	β	Std. Err.	t-stat	p-value	95 % CI
Automated control system (D_1)	+0,312	0,048	6,50	< 0,001	[0,217; 0,407]
Resident awareness (X_3)	+0,224	0,061	3,67	0,004	[0,103; 0,345]
Economically active residents (X_4)	+0,143	0,057	2,51	0,014	[0,030; 0,256]
Pre-2000 construction dummy (D_3)	+0,181	0,064	2,83	0,006	[0,054; 0,308]
Building construction year (X_2)	-0,112	0,043	-2,60	0,011	[-0,197; -0,027]
Number of households (X_6)	-0,178	0,052	-3,42	0,001	[-0,281; -0,075]
Constant	0,214	0,071	3,01	0,003	[0,073; 0,355]

Model fit: $R^2 = 0,61$; Adjusted $R^2 = 0,58$; $F(6,80) = 20,9$; $p < 0,001$, $n = 87$

Results and Discussion

RES Adoption Rates and Temporal Trends

Figure 1 presents actual RES adoption rates against the modelled technical potential for each city. Across all 87 buildings, the sample-average adoption rate in 2024 was 34,2 % $\pm$ 6,8 % (95 % CI: 31,4...37,0 %), representing less than half the technical potential of 78...85 % [12]. Yerevan recorded the highest rate (35,8 %), reflecting greater investment capacity and better HOA governance structures, while Gyumri lagged slightly at 31,4 % (fig.1).

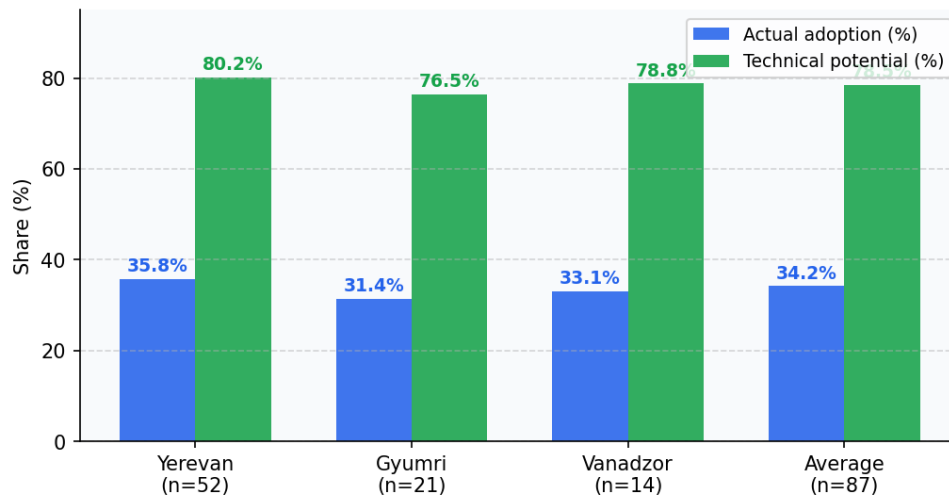


Fig. 1. Actual RES Adoption Rate vs. Technical Potential by City (2015–2024)

Fig. 2 traces the evolution of adoption over the study period. All three cities exhibited a near-linear upward trajectory from approximately 12 % in 2015, with annual incremental gains averaging 2,4 percentage points. The growth rate did not accelerate following the 2020 introduction of net-metering legislation, suggesting that regulatory reform alone is insufficient without accompanying technical and financial support [13].

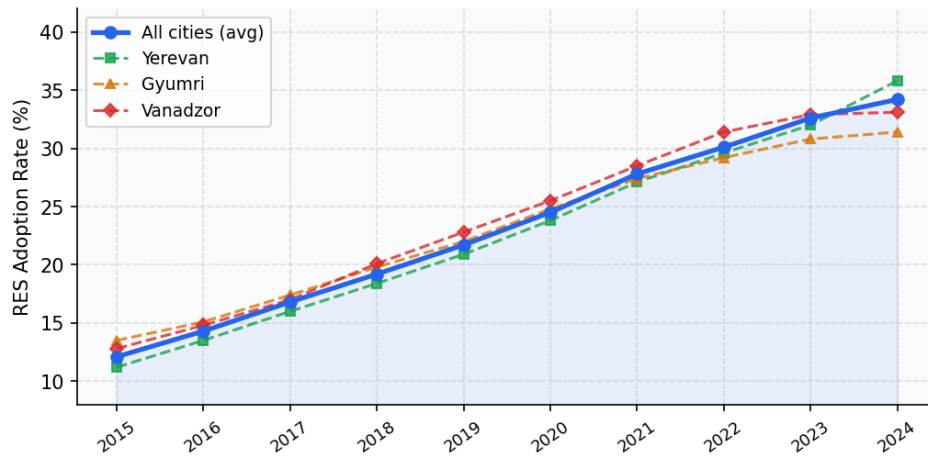


Fig. 2. RES Adoption Trend by City, 2015–2024

Distributional Inequality: Lorenz Analysis

Fig. 3 depicts the Lorenz curve for the pooled 2024 sample. The observed Gini coefficient ($G = 0,47$; $SD = 0,12$) is substantially above the comparator benchmark of $G = 0,30 \dots 0,35$ considered consistent with equitable collective energy management in the literature. The curve shows that the bottom 40 % of households received only 18 % of total RES-generated electricity, while the top 20 % captured 48 %. This skew is attributable primarily to unequal apartment-floor-area allocations, differential HOA participation, and heterogeneous appliance loads [14].

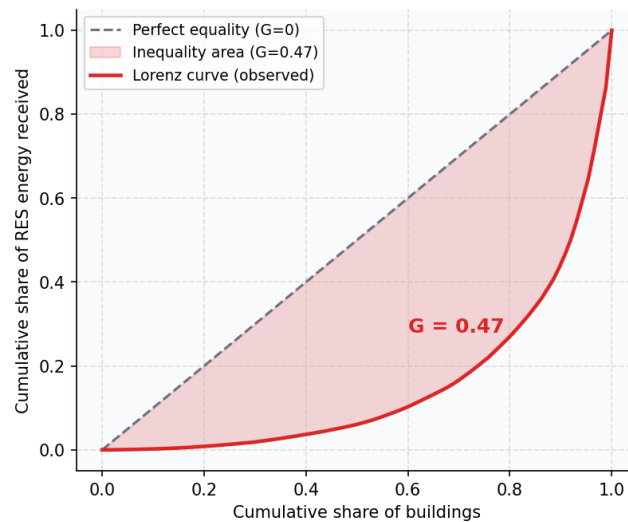


Fig. 3. Lorenz Curve of RES Energy Distribution ($G = 0,47$; $SD = 0,12$), pooled 2024 data

Cluster Typologies

K-Means analysis ($k = 3$) yielded three statistically distinct building typologies, visualised in Fig. 3:

- Cluster A — High-efficiency ($G < 0,30$; $n = 19$, mean adoption: 68,4 %): These buildings combine technical readiness (automated PV management, recent renovation) with strong social governance (active HOA, high awareness scores). They tend to be post-2000 constructions in Yerevan with 24...48 units.
- Cluster B — Intermediate ($G = 0,30 \dots 0,50$; $n = 43$; mean adoption: 38,7 %). The modal cluster. Key bottlenecks are insufficient resident awareness and the absence of transparent benefit-sharing

mechanisms. These buildings have the highest policy leverage, as targeted interventions could shift a substantial share into Cluster A (table 3).

- Cluster C — High-inequality ($G > 0,50$; $n = 25$; mean adoption: 19,2 %): Critical barriers include financial inaccessibility and unresolved legal disputes over co-ownership of rooftop space and shared infrastructure costs. Most are pre-1990 panel-construction (khrushchyovka / brezhnevka) buildings in Gyumri and Vanadzor (fig. 4).

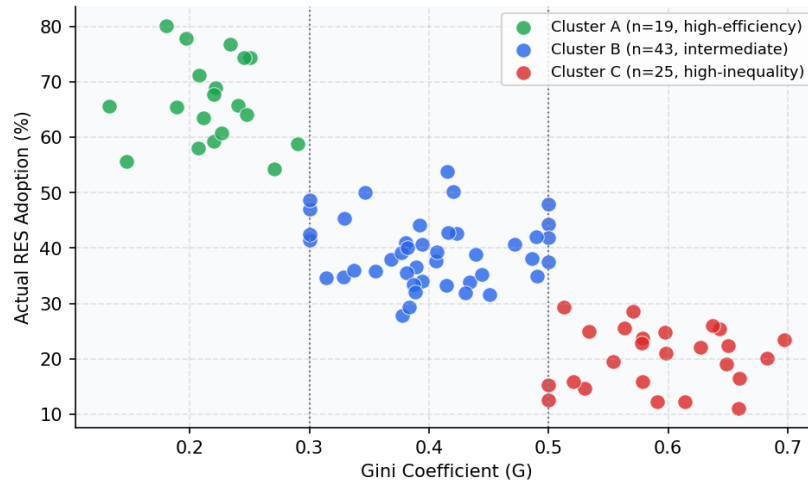


Fig. 4. K-Means Cluster Distribution ($k = 3$) by Gini Coefficient and RES Adoption Rate

Table 3

Cluster Profiles — Mean Values of Key Variables

Variable	Cluster A (n=19)	Cluster B (n=43)	Cluster C (n=25)
Mean Gini coefficient (G)	0,22	0,4	0,62
Mean RES adoption (%)	68,40	38,7	19,20
Automated control system (%)	94,70	55,8	12,0
Active HOA (%)	89,50	58,1	24,0
Mean awareness score (1–5)	4,10	3,0	1,90
Pre-2000 construction (%)	10,50	51,2	84,0
Received subsidy (%)	78,90	44,2	16,0

Regression Analysis

The OLS regression results (Table 2) explain 61% of variance in the Gini coefficient. Fig. 4 visualises the standardised coefficients. Three findings stand out:

Automated control systems ($\beta = +0,312$; $p < 0,001$) exert the strongest effect. Buildings equipped with automated distribution management show G values averaging 0,15 points lower than comparable unequipped buildings, after controlling for all other covariates. This is consistent with engineering-economics literature showing that real-time load balancing eliminates the manual-override behaviours that drive inequality [15].

Resident awareness ($\beta = +0,224$; $p < 0,01$) operates through a social-norm mechanism: higher awareness scores predict not only greater individual RES utilisation but also cooperative compliance with HOA-agreed distribution rules, reducing free-riding.

Building size ($\beta = -0,178$; $p < 0,01$) has a counter-intuitive negative sign. Larger buildings benefit from economies of scale in PV system management and governance, producing more equal per-household distribution despite the greater organizational complexity (fig. 4).

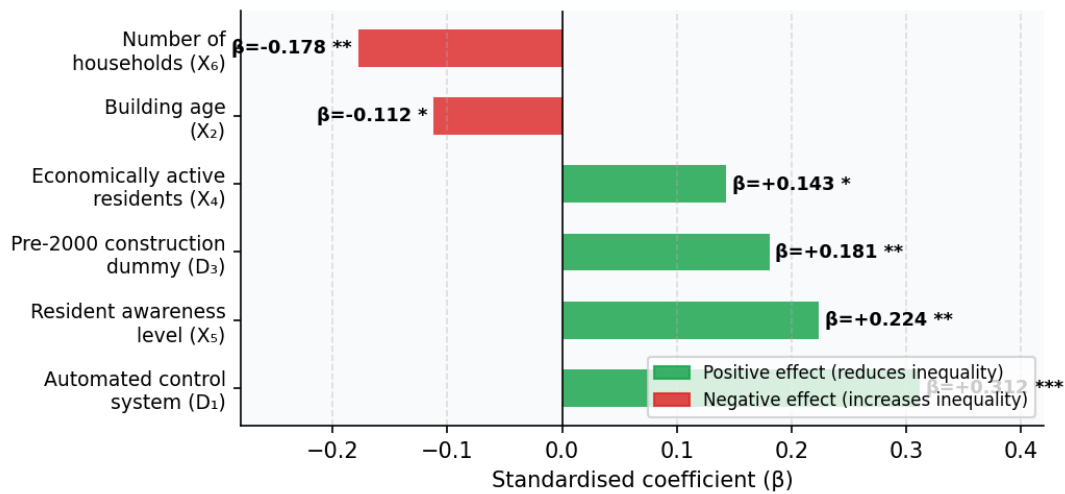


Fig. 4. Standardised OLS Coefficients for Predictors of the Gini Coefficient
(β with 95% confidence intervals; *** $p < 0,001$; ** $p < 0,01$; * $p < 0,05$)

Discussion

The 43...50 percentage-point gap between actual adoption (34,2 %) and technical potential (78...85 %) is not primarily a technology or cost problem — it is a governance and institutional problem. The Cluster A buildings demonstrate that near-70% adoption is achievable today with existing PV technology, provided that automated management and active HOA structures are in place [16]. The policy implication is clear: scaling Cluster A characteristics to Cluster B and C buildings should be the priority.

The high Gini value ($G = 0,47$) raises an equity concern that goes beyond efficiency: if RES benefits are disproportionately captured by wealthier or better-organised households within a building, the “green transition” risks deepening existing socio-economic divides rather than alleviating them. This distributional dimension has received insufficient attention in Armenian energy policy to date [17].

The finding that awareness mediates distribution efficiency suggests that social and educational interventions can complement technical ones at a fraction of the cost. A structured HOA capacity-building programme, estimated at USD 800...1200 per building, could shift a Cluster B building meaningfully towards Cluster A within one to two years — a highly cost-effective return relative to the capital expenditure of PV installations [18].

Limitations of the study include the cross-sectional nature of the regression analysis (which precludes strong causal inference), the reliance on self-reported awareness scores, and the exclusion of single-family suburban buildings from the sample. Future research should incorporate panel data designs and extend the analysis to rural multi-unit housing.

Conclusion

This study yields five principal conclusions with direct policy relevance:

1. The actual RES adoption rate of 34,2 % is less than half the technical-economic potential of 78...85%. The adoption gap is systematic and persistent across cities, construction eras, and building sizes, indicating structural rather than incidental barriers.
2. A Gini coefficient of 0,47 confirms high distributional inequality. Equity considerations must be embedded in RES deployment policy for the multi-apartment sector, not treated as a secondary concern.
3. Automated control systems are the single most powerful lever for improving both adoption rates and distributional equity. Priority public support for automated PV management installation is warranted, particularly for Cluster C buildings.
4. Resident awareness is a tractable, low-cost intermediate target. HOA capacity-building and community energy literacy programmes should be integrated into national RES deployment frameworks.
5. The 2025–2027 Smart Building pilot programme (n = 12 buildings, targets: adoption ≥ 45 %, $G \leq 0,18$) provides a scalable proof-of-concept. Rigorous mid-term evaluation is recommended to generate evidence for national rollout.

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**ԲԱԶՄԱԲՆԱԿԱՐԱՆ ՇԵՆՔԵՐՈՒՄ ՎԵՐԱԿԱՆՔՆՎՈՂ ԷՆԵՐԳԻԱՅԻ ԲԱՇԽՄԱՆ
ՀԻՄՆԱԽՆԴԻՐՆԵՐԸ ՀԱՅԱՍՏԱՆԻ ՏՎՅԱԼՆԵՐՈՎ (2015–2024)**

Սերգեյ Աշոտի Մինասյան, Մարիամ Արմենի Առաքելյան՝ Աշոտ Գևորգի Բաղդասարյան

Ճարտարապետության և շինարարության Հայաստանի ազգային համալսարան, ք. Երևան, ՀՀ

**mariamaraqelyan@nuaca.am*

Ուսումնասիրվել են վերականգնվող էներգիայի աղբյուրների (ՎԷԱ) տեղակայման և բաշխման հիմնախնդիրները Հայաստանի Հանրապետության բազմաբնակարան շենքերում: Հիմնվելով Երևան, Գյումրի և Վանաձոր քաղաքների 87 շենքերի (2015–2024 թթ.) տվյալների վրա՝ ուսումնասիրությունը քանակապես գնահատում է ՎԷԱ իրական և պոտենցիալ ներդրման միջև եղած բացը, չափում է բաշխման անհավասարությունը՝ օգտվելով Ջինիի գործակից, բացահայտում ներդրման հիմնական խոչընդոտները խառը մեթոդներով հարցման գործիքի միջոցով և մոդելավորում է բաշխման արդյունավետության կանխատեսիչները՝ օգտագործելով փոքրագույն քառակուսային (OLS) ռեգրեսիոն և $K_{\text{միջ}}$ խմբային վերլուծության գործակիցները: Արդյունքները ցույց են տալիս, որ ՎԷԱ իրական ներդրման մակարդակը կազմում է $34,2 \pm 6,8 \%$ ՝ $78...85 \%$ տեխնիկական պոտենցիալի դիմաց: Ջինիի գործակիցը ($G = 0,47$, $SD = 0,12$) բացահայտում է բաշխման էական անհավասարությունը: Ռեգրեսիոն մոդելը ($R^2 = 0,61$, $F(6,8)=20,9$, $p<0,001$) որպես գերիշխող գործոններ նույնականացնում է ավտոմատ կառավարման համակարգերը ($\beta = +0,312$, $p < 0,001$), բնակիչների իրազեկվածությունը ($\beta = +0,224$, $p < 0,01$) և տնային տնտեսությունների թիվը ($\beta = -0,178$, $p < 0,01$): Քննարկվում են քաղաքականության հետևանքները և 2025–2027 թթ. «Խելացի շենք» փորձնական ծրագիրը:

Բանալի բառեր. *վերականգնվող էներգիա, բազմաբնակարան շենք, Ջինիի գործակից, էներգիայի բաշխում, OLS ռեգրեսիա, խելացի շենք, Հայաստան*

ПРОБЛЕМЫ РАСПРЕДЕЛЕНИЯ ВОЗОБНОВЛЯЕМОЙ ЭНЕРГИИ В МНОГОКВАРТИРНЫХ ЗДАНИЯХ НА ОСНОВЕ ДАННЫХ ИЗ АРМЕНИИ (2015–2024)

Сергей Ашотович Минасян, Мариам Арменовна Аракелян*, Ашот Геворгович Багдасарян

Национальный университет архитектуры и строительства Армении, г. Ереван, РА

*mariamaraqelyan@nuaca.am

Исследуются проблемы внедрения и распределения возобновляемых источников энергии (ВИЭ) в многоквартирных жилых домах Республики Армения. На основе долгосрочных данных по 87 зданиям в г. Ереване, Гюмри и Ванадзоре (2015–2024 гг.) в исследовании количественно оценивается разрыв между фактическим и потенциальным внедрением ВИЭ, измеряется неравенство в распределении с помощью коэффициента Джини, определяются ключевые барьеры внедрения с помощью смешанного метода опроса и моделируются предикторы эффективности распределения с помощью методом регрессии наименьших квадратов (МНК) и кластерного анализа методом К-средних. Результаты показывают, что фактический уровень внедрения ВИЭ составляет $34,2\% \pm 6,8\%$ при техническом потенциале 78...85 %. Коэффициент Джини ($G = 0,47$, $SD = 0,12$) указывает на существенное неравенство в распределении. Регрессионная модель ($R^2 = 0,61$, $F(6,80) = 20,9$, $p < 0,001$) определяет автоматизированные системы управления ($\beta = +0,312$, $p < 0,001$), осведомленность жильцов ($\beta = +0,224$, $p < 0,01$) и количество домохозяйств ($\beta = -0,178$, $p < 0,01$) как доминирующие факторы. Обсуждаются политические последствия и пилотный проект «умного здания» на 2025–2027 годы.

Ключевые слова: возобновляемая энергия, многоквартирный дом, коэффициент Джини, распределение энергии, регрессия методом наименьших квадратов, интеллектуальное здание, Армения

Մինասյան Սերգեյ Աշոտի, և.գ.դ., պրոֆեսոր (ՀՀ, ք. Երևան) – ՀՀՀՀՀՀ, ՋԳՄՈ ամբիոն, (+374)91408689, sergey.minasyan@yahoo.com, **Առաքելյան Մարիամ Արմենի** (ՀՀ, ք. Երևան) – ՀՀՀՀՀՀ, ՋԳՄՈ ամբիոն, haygnr@nuaca.am, (+374)77890666, mariamaraqelyan@nuaca.am, **Բաղդասարյան Աշոտ Գևորգի** (ՀՀ, ք. Երևան) – ՀՀՀՀՀՀ, ՋԳՄՈ ամբիոն, byan.ashot@gmail.com, (+374)96333954, byan.ashot@gmail.com

Минасян Сергей Ашотович, д.т.н., профессор (РА, г. Ереван) - НУАСА, кафедра Теплогазоснабжения и вентиляции, (+374)91408689, sergey.minasyan@yahoo.com, **Аракелян Мариам Арменовна** (РА, г. Ереван) - НУАСА, кафедра Теплогазоснабжения и вентиляции, соискатель, (+374)77890666, mariamaraqelyan@nuaca.am, **Багдасарян Ашот Геворгович** (РА, г. Ереван) - НУАСА, кафедра Теплогазоснабжения и вентиляции, магистр, (+374)96333954, byan.ashot@gmail.com

Minasyan Sergey, doctor of science (engineering), professor (RA, Yerevan) - NUACA, Chair of ventilation, gas and heat supply, (+374)91408689, sergey.minasyan@yahoo.com, **Arakelyan Mariam** (RA, Yerevan) - NUACA, Chair of ventilation, gas and heat supply, postgraduate student, (+374)77890666, mariamaraqelyan@nuaca.am, **Bagdasaryan Ashot** (RA, Yerevan) - NUACA, Chair of ventilation, gas and heat supply, master, (+374)96333954, byan.ashot@gmail.com

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