Title: Analyzing the Impact of Renewable Energy Adoption on Traditional Energy Markets: A VAR and ARCH-GARCH Approach

Abstract:

This paper investigates the dynamic interactions between renewable energy adoption and traditional energy markets using a Vector Autoregression (VAR) and Autoregressive Conditional Heteroskedasticity (ARCH-GARCH) modeling approach. With the global shift towards sustainable energy, understanding the repercussions on existing energy structures is critical. Employing time-series data from 1990 to 2023, our VAR models elucidate the relationships between renewable energy consumption, particularly solar, and traditional energy variables such as fossil fuel consumption, nuclear power generation, and electricity pricing. The ARCH-GARCH models further explore the volatility within these markets, highlighting the persistence of volatility clustering. Our results indicate a strong explanatory and predictive power of the VAR models with significant interdependencies between energy types. Renewable energy adoption shows a positive impact on electricity prices, suggesting a transformative effect on the market structure. Meanwhile, traditional energy consumption demonstrates an inverse relationship with electricity prices, revealing a potential substitution effect. The implications of these findings are vast, covering policy-making, infrastructure development, and risk management strategies as the energy market transitions towards a greener future.

Introduction:

In recent decades, the global energy landscape has undergone a paradigm shift with the increased adoption of renewable energy sources. This shift, driven by the urgent need for sustainable energy solutions, poses profound implications for traditional energy markets. This paper employs an empirical approach using Vector Autoregression (VAR) and Autoregressive Conditional Heteroskedasticity (ARCH-GARCH) models to analyze the intricate dynamics between renewable energy consumption and traditional energy systems. By analyzing time-series data from 1990 to 2023, we examine the interplay between solar energy consumption and conventional energy metrics, including fossil fuel and nuclear power consumption, and their resultant effect on electricity pricing mechanisms. The study reveals pivotal insights into the transformative impact of renewable energy on market structure and the emerging substitution effects in energy consumption patterns. Through our investigation, we aim to illuminate the evolving role of renewable energy, delineate its influence on market volatility, and discuss the broader implications for energy policy, infrastructure adaptation, and strategic risk management in an era steering towards a greener future.

As we progress through the paper, we will explore each model in detail, unpacking the complex relationships and volatility patterns within the energy sector that emerge from our analysis.

Methodology:

Our study harnesses a rich dataset encompassing time-series data from 1990 to 2023. We source data on diverse energy consumption types—renewable, natural gas, and total energy—alongside economic indicators such as the federal funds rate, crude oil benchmark prices, and average energy prices to ultimate consumers.

We employ Vector Autoregression (VAR) models as our primary analytical tool to unravel the interdependencies between these energy sources and economic indicators. These models capture the dynamic interactions and enable us to trace the relationships over time.

The study also delves into the realm of volatility and shock analysis through ARCH-GARCH models. These models are pivotal in understanding how energy markets react to unexpected changes and disturbances, providing a deeper insight into market stability and risk.

This approach is methodically sequenced, beginning with the VAR models to establish baseline relationships, followed by the log-transformed VAR models to highlight elasticities and percentage changes in the data. We then transition to the VAR3 model, which elucidates the relationship between solar energy consumption and energy pricing. Lastly, we integrate the ARCH-GARCH models to dissect and forecast the volatility patterns that emerge, particularly in the wake of the impulse responses observed in the VAR3 model.

Each step of our methodology is designed to build upon the previous, creating a layered understanding of the market's complexity and the forward-looking implications of renewable energy integration into traditional energy markets.

Results:

VAR 1:

Vector Autoregression Estimates			
Date: 11/15/23 Time: 20:19			
Sample (adjusted): 1990M03 2023M07			
Included observations: 401 after adjustments			
Standard errors in ( ) & t-statistics in [ ]			
	TOTALFOSIL	NUCLEAR	SOLAR
TOTALFOSIL(-1)	0.390247	-0.036982	-3.11E-05
	-0.06194	-0.00679	-0.00037
	[6.30052]	[-5.44557]	[-0.08493]
TOTALFOSIL(-2)	-0.091683	-0.008764	0.002074
	-0.06205	-0.0068	-0.00037
	[-1.47757]	[-1.28826]	[5.64565]
NUCLEAR(-1)	1.126583	0.845197	0.000197
	-0.54594	-0.05986	-0.00323
	[2.06355]	[14.1199]	[0.06081]
NUCLEAR(-2)	-2.03734	-0.40264	-0.006328
	-0.52468	-0.05753	-0.00311
	[-3.88300]	[-6.99911]	[-2.03750]
SOLAR(-1)	-42.14541	-2.973495	1.594159
	-6.18507	-0.67815	-0.03661
	[-6.81406]	[-4.38474]	[43.5398]
SOLAR(-2)	43.54366	2.482953	-0.631268
	-6.2231	-0.68232	-0.03684
	[6.99710]	[3.63901]	[-17.1358]

C	3.932458	0.367594	-0.010763
	-0.281	-0.03081	-0.00166
	[13.9943]	[11.9310]	[-6.47054]
INDQ	0.030492	0.003885	-5.46E-05
	-0.00274	-0.0003	-1.60E-05
	[11.1087]	[12.9093]	[-3.35943]
APRICERES	-0.13575	-0.004041	0.000636
	-0.01983	-0.00217	-0.00012
	[-6.84453]	[-1.85809]	[5.41668]
R-squared	0.608434	0.765673	0.986868
Adj. R-squared	0.600443	0.760891	0.9866
Sum sq. resids	48.24611	0.579989	0.001691
S.E. equation	0.350823	0.038465	0.002077
F-statistic	76.13868	160.1092	3682.479
Log likelihood	-144.4063	742.0165	1912.509
Akaike AIC	0.765119	-3.655943	-9.493813
Schwarz SC	0.854759	-3.566303	-9.404173
Mean dependent	6.637077	0.650332	0.014238
S.D. dependent	0.555008	0.078663	0.017941
Determinant resid covariance (dof adj.)		4.27E-10	
Determinant resid covariance		3.99E-10	
Log likelihood		2632.273	
Akaike information criterion		-12.99388	
Schwarz criterion		-12.72496	
Number of coefficients		27	

VAR 2:

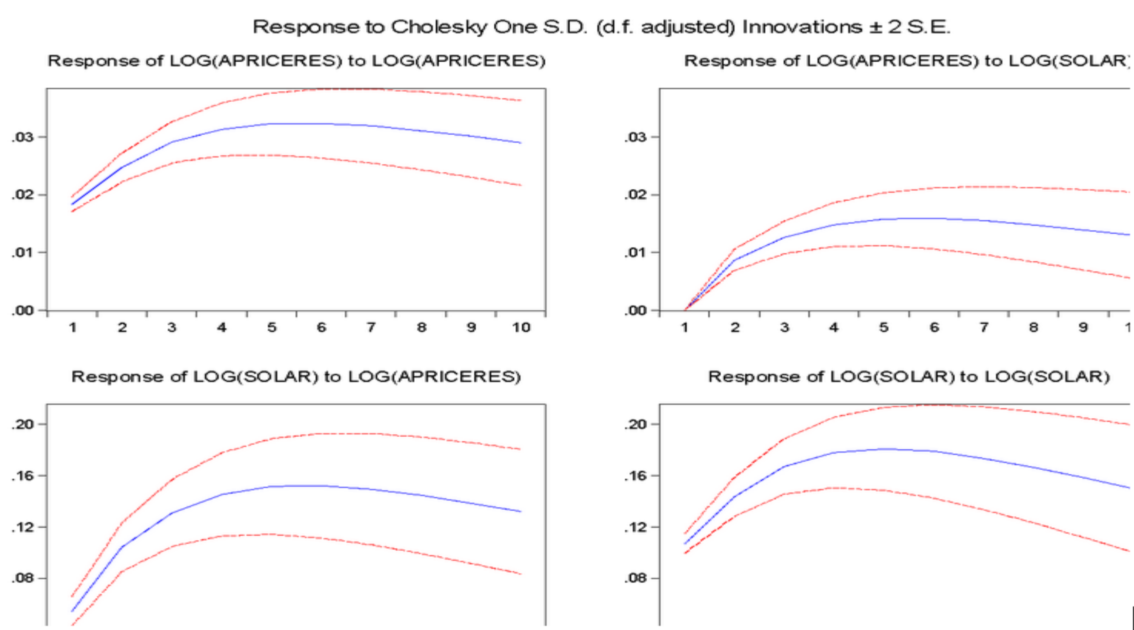
Vector Autoregression Estimates			
Date: 11/27/23 Time: 14:50			
Sample (adjusted): 1990M03 2023M07			
Included observations: 401 after adjustments			
Standard errors in ( ) & t-statistics in [ ]			
	LOG(TOTALFOSIL)	LOG(NUCLEAR)	LOG(SOLAR)
LOG(TOTALFOSIL(-1))	0.401784	-0.380023	-0.296773
	-0.0546	-0.06728	-0.11314
	[7.35801]	[-5.64797]	[-2.62296]
LOG(TOTALFOSIL(-2))	-0.086284	-0.080653	1.38747
	-0.05563	-0.06854	-0.11526
	[-1.55114]	[-1.17668]	[12.0378]
LOG(NUCLEAR(-1))	0.048991	0.794506	0.135914
	-0.04496	-0.0554	-0.09316
	[1.08960]	[14.3404]	[1.45886]
LOG(NUCLEAR(-2))	-0.198219	-0.412251	-0.269955
	-0.04347	-0.05356	-0.09007
	[-4.56018]	[-7.69682]	[-2.99728]
LOG(SOLAR(-1))	-0.210765	-0.168923	1.37352
	-0.01822	-0.02245	-0.03774
	[-11.5703]	[-7.52572]	[36.3899]
LOG(SOLAR(-2))	0.193303	0.138731	-0.385186
	-0.01766	-0.02176	-0.03658
	[10.9487]	[6.37693]	[-10.5291]
C	-0.246772	-1.868711	-1.198454

	-0.15869	-0.19554	-0.32882
	[-1.55502]	[-9.55647]	[-3.64471]
LOG(INDQ)	0.367364	0.503708	-0.384907
	-0.03064	-0.03776	-0.06349
	[11.9897]	[13.3414]	[-6.06270]
LOG(APRICERES)	-0.109192	0.028551	0.32358
	-0.02951	-0.03637	-0.06115
	[-3.69963]	[0.78506]	[5.29115]
R-squared	0.677217	0.791276	0.988248
Adj. R-squared	0.67063	0.787016	0.988008
Sum sq. resids	0.893508	1.356658	3.836173
S.E. equation	0.047743	0.058829	0.098925
F-statistic	102.805	185.7595	4120.47
Log likelihood	655.3711	571.6375	363.2276
Akaike AIC	-3.223796	-2.806172	-1.766721
Schwarz SC	-3.134156	-2.716532	-1.677081
Mean dependent	1.889212	-0.438083	-4.757249
S.D. dependent	0.083189	0.127473	0.903361
Determinant resid covariance (dof adj.)		4.81E-08	
Determinant resid covariance		4.50E-08	
Log likelihood		1684.97	
Akaike information criterion		-8.269179	
Schwarz criterion		-8.000258	
Number of coefficients		27	

VAR 3:

Vector Autoregression Estimates		
Date: 11/29/23 Time: 20:32		
Sample (adjusted): 1990M03 2023M07		
Included observations: 401 after adjustments		
Standard errors in ( ) & t-statistics in [ ]		
	LOG(APRICERES)	LOG(SOLAR)
LOG(APRICERES(-1))	1.103838	1.71567
	-0.05185	-0.33914
	[21.2892]	[5.05887]
LOG(APRICERES(-2))	-0.121503	-1.669675
	-0.0514	-0.3362
	[-2.36385]	[-4.96627]
LOG(SOLAR(-1))	0.081394	1.337366
	-0.00816	-0.05338
	[9.97405]	[25.0551]
LOG(SOLAR(-2))	-0.081121	-0.367627
	-0.00817	-0.05346
	[-9.92565]	[-6.87699]
C	-0.036013	-0.451669
	-0.03314	-0.21678
	[-1.08661]	[-2.08353]
LOG(INDQ)	0.017711	0.045089
	-0.00869	-0.05681
	[2.03924]	[0.79371]

R-squared	0.992523	0.982521
Adj. R-squared	0.992429	0.9823
Sum sq. resids	0.133359	5.70545
S.E. equation	0.018374	0.120184
F-statistic	10487.33	4440.81
Log likelihood	1036.744	283.6398
Akaike AIC	-5.14087	-1.384737
Schwarz SC	-5.08111	-1.324977
Mean dependent	2.332857	-4.757249
S.D. dependent	0.211169	0.903361
Determinant resid covariance (dof adj.)		3.88E-06
Determinant resid covariance		3.77E-06
Log likelihood		1366.033
Akaike information criterion		-6.753284
Schwarz criterion		-6.633764
Number of coefficients		12



ARCH-GARCH 1:

ARCH family regression

Sample: 01jan1990 thru 01jul2023, but with gaps

	Number of obs	=	403
	Wald chi2(6)	=	5371.24
Log likelihood = -393.5256	Prob > chi2	=	0.0000

AveragePriceofElectricityto	Coefficient	OPG std. err.	z	P>|z|	[95% conf.	interval]
AveragePriceofElectricityto						
TotalFossilFuelsConsumption	-.8690706	.0925409	-9.39	0.000	-1.050447	-.6876938
NuclearElectricPowerConsumpti	4.679717	.8226826	5.69	0.000	3.067289	6.292145
SolarEnergyConsumptionQuadri	59.4925	2.02692	29.35	0.000	55.51981	63.46519
FFERPercentMonthlyNotSeas	-.1343797	.0197723	-6.80	0.000	-.1731327	-.0956267
IndustrialProductionTotalInd	.034559	.0069579	4.97	0.000	.0209217	.0481962
CrudeOilPricesDollarsperBa	.0223109	.0017707	12.60	0.000	.0188403	.0257815
_cons	8.564299	.6424053	13.33	0.000	7.305207	9.82339
ARCH						
arch						
L1.	2.94e-08	.	.	.	.	.
garch						
L1.	2.94e-08	.	.	.	.	.
_cons	.4127569	.0299805	13.77	0.000	.3539963	.4715176

ARCH-GARCH 2:

ARCH family regression

Sample: 01jan1990 thru 01jul2023, but with gaps

	Number of obs	=	403
	Wald chi2(6)	=	1495.60
Log likelihood = 1343.265	Prob > chi2	=	0.0000

SolarEnergyConsumptionQuadri	Coefficient	OPG std. err.	z	P>|z|	[95% conf.	interval]
SolarEnergyConsumptionQuadri						
TotalFossilFuelsConsumption	.0034571	.0014163	2.44	0.015	.0006813	.006233
NuclearElectricPowerConsumpti	-.0374783	.0117002	-3.20	0.001	-.0604102	-.0145464
FFERPercentMonthlyNotSeas	.0016811	.0002429	6.92	0.000	.001205	.0021573
IndustrialProductionTotalInd	-.0000856	.0001067	-0.80	0.422	-.0002946	.0001234
AveragePriceofElectricityto	.0107435	.0004265	25.19	0.000	.0099076	.0115793
CrudeOilPricesDollarsperBa	-.0002546	.0000279	-9.14	0.000	-.0003092	-.0002
_cons	-.0816945	.0087118	-9.38	0.000	-.0987693	-.0646198
ARCH						
arch						
L1.	-1.86e-07	.	.	.	.	.
garch						
L1.	-1.86e-07	.	.	.	.	.
_cons	.0000745	5.21e-06	14.31	0.000	.0000643	.0000847

Discussion:

.1 VAR 1

The VAR 1 model includes key energy market variables like Total Fossil Fuels Consumption, Nuclear Electric Power Consumption, and Solar Energy Consumption. These are modeled with exogenous variables Crude Oil Benchmark Prices, Industry Production Index, and Average Price of Electricity to Ultimate Consumers Residential. The model accounts for the time series nature of the data by considering the lagged values of these variables, allowing for an assessment of how past values influence current levels.

The t-statistics provide a measure of the significance of each coefficient. For Fossil Fuel Consumption, there exists a statistically significant inverse relationship between the previous period of Solar Energy Consumption and current Fossil Fuel Consumption levels, with coefficients (-42.14541) and t-statistic (6.81406). There appears to be a positive relationship from Solar Energy Consumption lag two, with coefficients (43.54366) and t-statistic (6.99710), indicating intricate relationships and a non-linear impact of solar energy adoption on the greater Fossil Fuel Consumption Market. Notably, exogenous variables: Crude Oil Benchmark Prices, Industrial Production, and Average Price for Residential; contain statistically significant effects on Fossil Fuel Consumption with an inverse relationship between Average Prices for Residential and Fossil Fuel Consumption. The overall fit of the model with Fossil Fuel Consumption as the dependent variable, shows the R-squared value of 0.608 indicating a moderate fit, suggesting that there are other factors not included in the model that also affect this side of the model.

For Solar Energy Consumption, there exists a statistically significant positive correlation between lag two periods of Fossil Fuel consumption and current Solar Energy Consumption, reinforcing the complex interplay between the two energy markets. Notably, the coefficients for Solar Energy Consumption at lag one (1.594159) with a t-statistic (43.5398), indicate patterns of Solar Energy adoption are largely dependent on previous periods of adoption. Exogenous variables: Crude Oil Benchmark Prices, Industrial Production, and Average Price for Residential; contain statistically significant t-statistic (5.41668) with a positive correlation between Average Prices for Residential and Solar Energy Consumption. The overall fit of the model with Solar Energy Consumption as the dependent variable, shows the R-squared value of 0.986868 indicating a good fit for the model, suggesting that the model explains a substantial portion of the variability for Solar Energy consumption.

.2 VAR 2

The VAR 2 model extends our analysis to log-transformed variables of Total Fossil Fuel Consumption, Nuclear Electric Power Consumption, and Solar Energy Consumption, integrating the same exogenous factors as VAR 1. By analyzing the log-transformed values, we emphasize the elastic relationships and interpret the model coefficients as elasticities, which indicate percent change in the dependent variable for a one percent change in the independent variable.

In this model, the log-transformed values of log-transformed lagged values of Solar Energy Consumption and Total Fossil Fuels Consumption exhibit significant coefficients, illustrating the complex and elastic relationships within the energy market. For instance, the coefficient for LOG(SOLAR(-1)) with a t-statistic (-11.5703) indicates a robust negative elasticity, showing that past solar energy consumption is a significant predictor of current trends for the Fossil Fuel energy market. Furthermore, the exogenous variable of Industrial Production, shows a significantly significant positive relationship with current Fossil Fuel Consumption. The R-squared value for the log-transformed Total Fossil Fuels Consumption model is 0.677217, suggesting that the model explains approximately 67.7% of the variance and provides a moderate fit.

On the Solar Energy Consumption side of the model, there is a statistically significant positive correlation between LOG(TOTALFOSIL(-2)) indicating past Fossil Fuel Consumption is a significant predictor of current trends in the Solar Energy market. Most notably, there appears to be a significantly significant (t-stat: 5.29115) positive correlation of elasticity between Average Prices for Residential and Solar Energy Consumption, with a 1% increase in LOG(APRICERES) correlating with a 0.32358% increase in LOG(SOLAR). The R-squared value of 0.988248 implies an excellent fit, indicating that the model explains a vast majority of the variability for Solar Energy consumption. Overall, the VAR 2 model complements the VAR 1 analysis by offering a deeper understanding of the proportional changes and interdependencies in energy consumption and pricing.

.3 VAR 3 & Impulse Analysis

The VAR 3 model delves deeper into the dynamics between solar energy consumption and the average price of electricity to residential customers, employing log-transformed values to capture elasticities and percent changes. This model provides insight for assessing the immediate and delayed impacts of solar energy adoption on electricity pricing. In this model, we employ Average Price for Residential and Solar Energy Consumption as our dependent variables, with 2 lags to illustrate the effects over time; with exogenous variables of Crude Oil Benchmark Price and log transformed Industrial Production. We find high R-squared values of (0.992523 and 0.982521) respectively, indicating that the model explains a vast majority of the variability in both the average price of residential electricity and solar energy consumption.

There exists a positive correlation between LOG(SOLAR(-1)) with a coefficient (0.081394) with a significant t-statistic (9.97405), indicating that previous periods of solar energy consumption positively impact the current average residential electricity price. This suggests that as solar energy consumption increases, it leads to an increase in the average price of residential electricity, possibly due to infrastructure costs or other complex market dynamics that will require additional inquiry. Furthermore, there appears to be a delayed impact; the model also shows a negative coefficient for LOG(SOLAR(-2)) (-0.081121) with a significant t-statistic (-9.924565), suggesting a delayed inverse relationship between solar energy consumption and electricity pricing. This could reflect market adjustments or changes in supply-demand dynamics over time.

On the Solar Energy Consumption side of this model, we note a statistically significant positive relationship between the lag one Average Price for Residential and Solar Energy Consumption, with coefficient (1.71567) and t-statistic (5.05887); indicating that for a 1% increase in prices in the previous period, leads to a 1.71567% increase in Solar Energy Consumption. There is also a delayed impact, with a negative coefficient for LOG(APRICERES(-2)) (-1.669675), suggesting a delayed inverse relationship between previous electricity prices and solar energy consumption.

To illustrate these changes over time, we designed impulse response functions from VAR model 3, depicting the response of the average price of electricity to residential customers (LOG(APRICERES)) and solar energy consumption (LOG(SOLAR)) to one standard deviation shocks in each other over time.

- Response of LOG(APRICERES) to LOG(APRICERES): This shows the response of electricity prices to their own shock. The graph indicates that a shock in the price leads to an initial increase and then stabilizes over time. This suggests that the market may experience short-term volatility in prices, but tends to return to a steady state, reflecting a degree of price elasticity.

- Response of LOG(APRICERES) to LOG(SOLAR): Here we see the effect of a shock in solar energy consumption on the price of electricity. The graph shows an increasing trend, which means that an unexpected increase in solar energy consumption leads to a rise in electricity prices over time. This could be due to a variety of factors, such as increased demand for solar energy leading to higher costs or investment in infrastructure.
- Response of LOG(SOLAR) to LOG(APRICERES): Conversely, this graph shows how solar energy consumption responds to a shock in electricity prices. The trend is upward, indicating that as electricity prices rise, so does the consumption of solar energy, possibly reflecting a shift towards solar energy when traditional electricity becomes more expensive.
- Response of LOG(SOLAR) to LOG(SOLAR): This impulse response function shows the effect of a shock in solar energy consumption on itself. The initial increase followed by a plateau suggests that while solar energy consumption is impacted by its own shocks, it may have a self-correcting mechanism that stabilizes consumption over time.

The Var 3 model's impulse response functions show that shocks in solar energy consumption and electricity prices have time-dependent effects on each other. These results lead naturally into an analysis of how these shocks affect market volatility. The ARCH-GARCH models allow us to quantify and forecast the variance (volatility) around the expected mean levels predicted by the VAR models. This is particularly relevant in energy markets where prices and consumption can be highly volatile, and where understanding the magnitude and persistence of this volatility is crucial for risk management.

.4 ARCH-GARCH 1

In the ARCH-GARCH 1 model, we employ the average price for residential consumers as the dependent variable, with independent variables: Total Fossil Fuel Consumption, Nuclear Electric Power Consumption, Solar Energy Consumption, Federal Funds Effective Rate, Industrial Production, and Crude Oil Benchmark Prices. We acknowledge that the model has a substantial log likelihood of -393.5256, implying a good fit to the observed data. Additionally, the Wald chi-square statistic is extremely high (5371.24), indicating that the overall model is highly significant.

As observed, the negative coefficient for Total Fossil Fuels Consumption (-0.8690607) with a highly significant z-statistic (-.9.39) suggests that as the average price of electricity increases, the consumption of fossil fuels decreases. This could indicate that higher electricity prices may incentivize the use of alternative energy solutions. The positive coefficient for Nuclear Electric Power Consumption (4.679717) with a z-statistic (5.69) implies a strong positive elasticity, meaning higher electricity prices are associated with increased centralized nuclear power consumption.

Most notably, a very high positive coefficient for Solar Energy Consumption (59.4925) with a significant z-statistic (29.35) indicates a substantial increase in solar energy consumption with increasing average electricity prices. This could reflect a shift toward solar power as electricity prices rise, possibly due to solar being seen as a more cost-effective alternative. These findings may reveal a substitution effect, where higher electricity prices drive consumers to reduce usage or switch to alternative energy sources. Additionally, the ARCH term (2.94e-08) is small but significant, indicating that there is some level of immediate impact from shocks to volatility in the average price of electricity. The GARCH term (2.94e-08) suggests that volatility is persistent over time. This persistence means that any shocks to the system will have lasting effects on the volatility of electricity prices.

.5 ARCH-GARCH 2

In the ARCH-GARCH 2 model, we employ Solar Energy Consumption as the dependent variable, with independent variables: Total Fossil Fuels Consumption, Nuclear Electric Power Consumption, Federal Funds Effective Rate, Industrial Production, Average Price of Electricity for Residential, and Crude Oil Benchmark Price. We acknowledge that the model has a substantial log likelihood of 1343.265, implying a good fit to the observed data. Additionally, the Wald chi-square statistic is extremely high (1495.60), indicating that the overall model is highly significant.

Most notably, a very high positive coefficient for Average Price of Electricity (25.19) with a significant z-statistic (25.19) indicates a substantial increase in prices for residential consumers with increasing solar energy consumption. This reinforces the observed shift toward solar power as electricity prices rise. Additionally, crude oil benchmark prices seem to have a statistically significant z-statistic (-9.14) coefficient; implying there is a negative correlation between oil price and Solar energy consumption.

Curiously, the ARCH-GARCH values are negative (-1.86e-07 respectively). Typically, ARCH and GARCH coefficients measure the impact of previous period's effect and the current period's conditional volatility. A negative coefficient suggests a potential reduction in volatility with an increase in the lagged error terms or conditional variance. This could be a result of a model misspecification, an indication of mean reversion in volatility, or the influence of other complex market dynamics that are not captured in this model. Further investigation would be necessary to properly interpret this result.

Conclusion:

Our comprehensive analysis through VAR and ARCH-GARCH models reveals a significant transition in energy markets towards renewable sources, particularly solar. The models demonstrate a strong interplay between renewable adoption and traditional energy variables, with implications for consumption patterns, price elasticity, and market volatility. Notably, the positive impact of renewable energy adoption on electricity prices suggests an evolving market dynamic that favors sustainable solutions. As homeowners increasingly become participants in energy generation, the findings advocate for a future where decentralized, renewable energy systems play a pivotal role in shaping sustainable and resilient energy markets. This study underscores the need for strategic policy and infrastructure development that accommodate the growing influence of renewable energy, ensuring a smooth transition towards a more sustainable energy paradigm.