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Hedging Effectiveness on the MISO Exchange

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ABSTRACT

The purpose of this paper is to evaluate the effectiveness of four commonly used hedging techniques on wholesale electricity prices within the midcontinent independent system operator (MISO) energy market. This analysis provides and in-depth assessment of hedging performance on one of the largest power markets in North America. In a break from extant literature, hourly time series are used to create hedge portfolios for each of the regional hubs within the MISO footprint. Each risk management strategy is employed on 24 hourly time series for each of the eight regional hubs within the MISO footprint. This results in a total of 768 hedged portfolios across 192 hourly time series. While the naïve approach tends to outperform the others in terms of variance reduction, none of the strategies examined meet the generally accepted standard for a highly effective hedge. In several instances, the hedged portfolio contains a higher amount of risk than the unhedged position. This may be explained by the unique characteristics of wholesale electricity and hedging pressure, particularly during peak demand hours.

Keywords: Risk Management, Midwest Independent System Operator, Electricity Derivatives
JEL Classifications: G10, G20, G32

1. INTRODUCTION

Established as a regional transmission operator (RTO) in 2013, MISO is responsible for managing the flow of electricity across 15 states and one Canadian province (Manitoba). In addition to coordinating electricity flows and planning for the long-term reliability of the grid system within its footprint, MISO administers a market for trading wholesale electricity. Since the value of electricity varies by location, the market is divided into 8 regional hubs: Arkansas (AR), Illinois (IL), Indiana (IN), Louisiana (LA), Michigan (MI), Minnesota (MN), Mississippi (MS), and Texas (TX). Each hub has a distinct market for trading spot (real-time) and forward (day-ahead) electricity. Market clearing prices for day-ahead (DA) and real-time (RT) power, referred to as locational marginal prices (LMPs), are quoted in terms of dollars per megawatt hour ($/MWh). Every day, MISO aggregates nodal LMPs to hourly, hub-level LMPs and posts 24 day-ahead and 24 real-time LMPs for each of its 8 hubs. MISO is geographically the largest RTO in North America with 72,000 miles of transmission lines within its footprint and its wholesale power market is one of the largest in the world with over $40 billion cleared in 2022 (MISO fact sheet, 2023).

While the Financial Accounting Standards Board (FASB) stipulates that a hedge must be deemed highly effective to qualify for hedge accounting, practitioners are afforded some flexibility in operationalizing the concept. A variance reduction approach is often used to measure hedging efficacy both in research and in practice. Specifically, a hedge is generally regarded as highly effective if it reduces variance by at least 80% as compared to the unhedged position.

Deregulated electricity markets are a relatively recent phenomenon and research that evaluates hedging performance within these exchanges is limited. This study represents the first attempt to measure hedging performance on a hub-level basis for one of the largest wholesale electricity markets in North America. The rest of this paper is organized as follows. Section 2 provides a literature review. Section 3 presents the methodology. Section 4 provides the results and Section 5 concludes.

2. LITERATURE REVIEW

Most of the existing literature on hedging wholesale electricity focuses on the older, European deregulated power markets. Bystrom (2003) employs several techniques to measure the effectiveness of short-term hedging on the Nordic Power Exchange, Nord Pool. His sample includes daily spot and futures prices from 1996 to 1999, which are used to create weekly hedged portfolios. While Bystrom (2003) finds that static hedges (naïve and minimum variance) tend to outperform the dynamic GARCH models, none of the strategies meet the standard for a highly effective hedge. He reports that hedging typically results in a variance reduction of less than 20%. In one instance, hedging via orthogonal GARCH results in a higher variance than the unhedged position.

Hanly et al. (2017) evaluate the effectiveness of minimum variance and constant correlation GARCH (CCGARCH) models on three European electricity markets. The authors use daily spot and futures prices from each market during 2004 to 2014 to create weekly and monthly hedges. Although the monthly portfolios tend to perform better than weekly portfolios in terms of out-of-sample variance reduction, neither hedging horizon results in a variance reduction of at least 80%. Weekly minimum variance and CCGARCH hedged portfolios result in a higher variance than the unhedged position for one of the three markets in their study (Nord Pool).

Boroumand et al. (2019) simulate intra-day hedging strategies on the German-Austrian power market. The authors approach hedging through the lens of market participants that have a short position in wholesale electricity (i.e., retailers) and measure uncertainty with conditional value at risk and portfolio variance. They pair actual spot price and retail volumes on the German-Austrian market from 2013 to 2015 with simulated values for derivative contracts (forwards and options) and power plants. The authors evaluate nine hedging strategies across four intra-day clusters (9 am, 12 pm, 6 pm, 9 pm) and find that the most effective hedging approach varies between the clusters. Their simulations reveal that hedging generally results in modest risk reduction. As noted in previous studies, Boroumand et al. (2019) find hedging can lead to an increase in variance over the unhedged portfolio.

Pena (2023) applies several hedging techniques to Spanish exchange traded electricity futures contracts over monthly and annual investment horizons. In addition to the minimum variance strategy, Pena (2023) employs two other methods that are directly related to it: the Ederington and Salas (2008) hedge (which creates an optimal hedge ratio based on the assumption of partially predictable spot price movements), and another approach allows the variances and covariances between spot and futures prices to fluctuate through time. The naïve strategy and a BEKK (1,1) model are also utilized. The out of sample effectiveness of each strategy was limited, which the author contributes to the variation in correlation between spot and futures price changes.

Bonaldo et al. (2022) examine the relationship between spot and futures prices of four European nations: France, Germany, Italy, and Switzerland from 2010 to 2019. The comparison was performed over three time periods (monthly, quarterly, and yearly) and for base and peak load delivery (except for Switzerland, where only base load contracts were available). The authors report that futures prices do not converge to spot prices for any of the four countries. Surprisingly forward premiums for base delivery generally increased as the operating date approached the futures expiration date.

The lack of hedging efficacy and persistent forward premia found in wholesale electricity markets globally may in part be explained by Hesamzadeh et al. (2020). The authors outline how dominant power generators may create a disconnect between current forward prices and expected future spot prices in wholesale electricity markets. The effect that generators with market power have on spot and forward prices is magnified by asymmetric information, as market participants are usually unaware of the hedging positions employed by large generators. Motivated by a series of actions by one of Australia's largest generators and the resulting effects on spot prices, the Hesamzadeh et al. (2020) develop a model to explain hedging decisions for generators with market power. Their model shows electricity markets which are dominated by a few large generators whose hedged positions are unknown to other market participants will experience volatile spot and forward prices and, at the extreme, can create an environment where no equilibrium hedging position exists.

In one of the few studies of hedging performance in US power markets, Tanlapco et al. (2002) use direct and cross hedging strategies in four US power markets from 1998 to 2000. None of the direct or cross hedging approaches are highly effective and some result in a greater amount of risk compared to being unhedged.

This study provides two major contributions to extant literature. First, this research adds to the extremely scarce coverage of hedging efficacy in US wholesale electricity markets. Secondly, hedging efficacy is measured on an hourly and hub-level basis, which provides a unique layer of granularity.

3. DATA AND METHODOLOGY

The aim of this research is to investigate the out-of-sample performance of four hedging strategies on the MISO exchange: naïve, minimum variance (MV), autoregressive distributed lag (ARDL), and generalized autoregressive conditional heteroskedasticity (GARCH). The naïve hedging strategy is perhaps the most straightforward to implement as it assumes market participants offset the price risk associated with their long (short) position in the real-time market by shorting (buying) an equal number of megawatt hours in the day-ahead market. Naturally, the naïve hedge ratio (size of the hedge/size of the exposure) must equal 1.

The MV hedging technique proposed by Ederington (1979) is employed as follows:

$$\Delta RT_{i,j} = \alpha + \beta_{MVi,j} \Delta DA_{i,j} + e_t, \quad (1)$$

where $\Delta RT_{i,j}$ and $\Delta DA_{i,j}$ represent the respective 1-week change (in terms of \$/MWh) in real-time and day-ahead LMPs for power on hub i in hour j. The MV hedge ratio for hub i in hour j is denoted as $\beta_{MVi,j}$.

While the autoregressive distributed lag (ARDL) model described by Pesaran (1997) is not as prevalent in the risk management literature as the other three techniques evaluated in this paper, it does have some unique characteristics that may be beneficial to wholesale electricity market participants. Unlike the naïve, minimum variance, and GARCH models, ARDL(p,r) models yield both a long-run and a short-run relationship between real-time and day-ahead prices. Although the error correction model (ECM) described by Engle and Granger (1987) can also provide long-term and short-term relationships between RT and DA prices, it rests on the assumption that both price series are non-stationary. However, Knittel and Roberts (2005), Ciarreta et al. (2017), Junttila et al. (2018), among several others, report spot and forward prices on various electricity exchanges are stationary in levels. The ARDL model can still be applied to time series that oscillate about a long-term mean. The p term represents the order of the autoregressive component of the model, while the r term is the distributed lag component. The ARDL (1,1) model is expressed as follows:

$$\Delta RT_{i,j} = \alpha_1 + \alpha_2 RT_{i,jt-1} + \alpha_3 DA_{i,jt-1} + \beta_{ARDLi,j} \Delta DA_{i,j} + v_t \quad (2)$$

$RT_{i,j_{t-1}}$ and $DA_{i,j_{t-1}}$ represent the one-period lagged real-time and day-ahead LMP on hub in hour j, respectively. The long-run hedge ratio is calculated as $-\alpha_3/\alpha_2$. This study applies the ARDL (1,1) short-run hedge ratio estimate, $\beta_{ARDLi,j}$, to assess the model's ability to reduce price risk on the MISO exchange.

Given that time series in general, and electricity prices specifically, are oftentimes heteroskedastic, the GARCH (1,1) model introduced by Bollerslev (1986) is also employed in this analysis. The mean equation is described as:

$$\Delta RT_{i,j} = \alpha + \beta_{GARCHi,j} \Delta DA_{i,j} + e_t \quad (3)$$

The error term (e_t) in Equation 3 is expected to fluctuate based on information received in the previous period as follows:

$$e_t \mid \varphi_{t-1} \sim N\left(\sigma_t^2\right) \quad (4)$$

$$\sigma_t^2 = \alpha_0 + \delta_1 \sigma_{t-1}^2 + \gamma_1 e_{t-1}^2 \quad (5)$$

α_0 reflects the long-run average variance. σ_{t-1}^2 (GARCH term) represents the previous period's forecast variance and e_{t-1}^2 r(ARCH term) reflects information regarding volatility obtained in the previous period. The optimal hedge ratio, $\beta_{GARCHi,j}$, minimizes the conditional variance of the hedge portfolio.

The sample used in this study consists of hub-level day-ahead and real-time LMPs from January 01, 2018 to December 31, 2022. Weekly portfolios are constructed to evaluate hedging performance for each hour of the day, across all eight MISO hubs. All pricing information used in this analysis is available on MISO's website (www.misoenergy.org).

MV, ARDL, and GARCH hedge ratios are calculated using an 8-week rolling windows estimation period. Each week, the oldest real-time and day-ahead dollar returns are replaced with their current week's counterparts. The hedge ratios estimated in week t are then used to create a hedged portfolio in week $t+1$. This process is repeated throughout the sample period and results in a total of 252 weekly hedged portfolios for each hour of the day on every hub within the MISO footprint.

The out-of-sample hedging performance for each strategy is measured by percentage variance reduction as compared to the unhedged position ($\Delta RT_{i,j}$):

$$\%\,reduction = 1 - \left(\frac{\sigma^2_{hedged\ portfolio\,i,j}}{\sigma^2_{unhedged\ portfolio\,i,j}} \right). \quad (6)$$

$\sigma^2_{unhedged\ portfolio\,i,j}$ is defined as the variance in weekly real-time returns (in terms of \$/MWh) on hub in hour j. Equation 6 is applied to each of the 1-week hedged portfolios for all 24 of the hourly time series created for each of the 8 MISO hubs. Since four hedging strategies are employed per hourly time series, 96 hedged portfolios are created per hub. Overall, a total of 768 hedged portfolios are assessed across 192 hourly time series. This level of granularity is critical given that time and location are key components in the price formation process for wholesale electricity. Furthermore, the simulation results reported by Boroumand et al. (2019) suggest that hedging effectiveness may vary throughout the day.

Table 1 shows the descriptive statistics for hourly DA and RT LMPs on the exchange. Since the generalizations which follow also apply hub-level descriptive statistics, Table 1 reports aggregate LMP summary statistics across the entire footprint for brevity. While the real-time and day-ahead price series have similar means, the former is more volatile. As expected, average DA and RT LMPs are higher during peak hours (06:00 EST-21:00 EST) on the exchange. The average DA price for electricity during peak hours is \$39.74 per megawatt hour as compared to \$27.65 during off-peak hours, for peak/off-peak spread of \$12.09. The mean price for real-time power during peak hours is \$39.33 as compared to \$26.95 during off-peak hours, which results in a spread of \$12.37/MWh. Volatility is also greater during peak demand hours in both markets. Neither series is normally distributed, and the Augmented Dickey-Fuller (ADF) null hypothesis of a unit root is rejected for each hour of the day for both time series.

The following Table 1 shows descriptive statistics for hourly DA and RT LMPs across all 8 hubs within the MISO footprint. The augmented Dickey-Fuller (ADF) test was performed with 4 lags and a time trend coefficient.

4. RESULTS

Tables 2-9 show the variance reduction obtained from applying each hedging approach to the 24 hourly time series for each MISO hub. Only 91% (7/768) of total portfolios constructed meet the 80% variance reduction threshold commonly used to classify a hedge as highly effective. All of the 7 highly effective hedges occur on the Texas hub between the off-peak hours of 22:00-23:00. Overall, hedging tends to be most effective in Texas. The 24-h average variance reduction per technique

Table 1: Descriptive statistics

Hour	Mean DA ($/MWh)	SD DA ($/MWh)	Skew. DA	Kurt. DA	ADF DA	Mean RT ($/MWh)	SD RT ($/MWh)	Skew. RT	Kurt. RT	ADF RT
0:00	27.87	17.39	4.79	55.81	−9.83*	27.07	18.30	4.67	57.94	−11.06*
1:00	26.28	15.68	4.58	54.82	−9.97*	25.64	17.51	5.99	114.84	−10.64*
2:00	25.46	15.09	4.85	60.83	−9.93*	24.73	16.61	6.17	128.70	−10.64*
3:00	25.35	15.31	5.22	68.71	−10.16*	24.59	16.75	6.89	157.35	−10.94*
4:00	26.28	16.42	5.89	85.86	−10.30*	25.71	20.15	10.53	286.28	−12.02*
5:00	29.09	18.78	5.91	85.65	−10.38*	28.40	22.40	8.75	212.68	−11.78*
6:00	33.23	26.35	10.04	215.90	−11.91*	32.36	29.65	8.97	176.15	−13.00*
7:00	37.02	34.63	12.40	287.98	−12.94*	36.53	44.23	10.07	160.86	−14.62*
8:00	36.66	30.16	10.60	205.79	−12.16*	36.01	45.64	17.93	477.52	−15.45*
9:00	37.37	29.39	10.44	212.84	−11.63*	36.76	38.13	13.83	347.90	−14.17*
10:00	37.88	26.62	7.71	127.94	−10.72*	37.82	39.59	12.34	259.44	−14.25*
11:00	38.38	25.56	6.01	91.28	−9.68*	38.13	35.66	9.37	166.87	−12.93*
12:00	39.24	25.97	5.03	69.00	−8.96*	38.89	42.17	11.87	272.91	−12.96*
13:00	40.62	26.89	3.94	38.41	−8.20*	39.71	42.97	9.38	208.82	−11.99*
14:00	41.93	28.81	3.87	40.76	−7.87*	40.21	42.11	7.90	172.55	−10.47*
15:00	43.97	31.15	3.40	30.99	−7.40*	43.01	53.95	12.30	289.54	−11.97*
16:00	44.91	32.05	3.50	34.05	−7.33*	44.48	66.39	19.34	572.83	−14.47*
17:00	44.87	29.78	3.35	28.16	−7.97*	44.68	68.74	21.00	627.73	−15.41*
18:00	44.33	28.66	4.03	44.15	−8.92*	44.57	61.23	16.54	443.12	−15.10*
19:00	41.95	28.16	5.99	93.72	−9.81*	42.13	52.44	10.71	199.65	−14.68*
20:00	38.78	26.14	6.44	108.57	−9.87*	38.90	62.54	19.03	565.02	−15.18*
21:00	34.68	23.54	7.10	129.99	−10.23*	35.02	63.07	20.64	657.53	−15.25*
22:00	31.56	19.39	4.88	64.45	−9.49*	31.00	29.71	10.22	259.22	−12.58*
23:00	29.30	17.21	3.94	43.20	−8.72*	28.47	18.84	4.73	57.32	−10.02*
AVG	**35.71**	**24.55**	**6.00**	**94.95**	**−9.76***	**35.20**	**39.53**	**11.63**	**286.37**	**−12.98***

*Significant at 5% level. Hub-level summary statistics are available upon request.

Table 2: Out of sample variance-Arkansas Hub

Hour	$\sigma^2_{Unhedged}$	Naïve (%)	MV (%)	ARDL (1,1) (%)	GARCH (1,1) (%)
0:00	45.81	**39.25**	35.67	33.46	31.02
1:00	46.12	**34.97**	30.75	34.41	27.32
2:00	75.15	**34.30**	28.40	28.97	23.50
3:00	60.3	**43.28**	30.65	32.29	32.80
4:00	109.54	**32.76**	21.03	19.98	25.95
5:00	119.62	**19.29**	3.76	11.15	10.93
6:00	1426.35	**5.48**	−22.40	−34.41	−6.78
7:00	3737.3	**6.72**	−10.96	−18.07	−5.28
8:00	350.64	**34.88**	22.84	17.46	21.08
9:00	986.67	28.46	**44.06**	42.81	37.30
10:00	3291.76	17.58	36.45	**36.69**	33.68
11:00	993.54	25.41	**43.49**	40.30	33.80
12:00	3399.61	**15.08**	13.24	12.81	14.94
13:00	1195.85	22.67	**33.32**	29.46	33.10
14:00	1299.62	26.72	**43.13**	27.69	42.58
15:00	2122.68	**16.36**	5.35	−3.39	6.94
16:00	1374.56	**26.04**	17.44	12.06	22.87
17:00	1886.82	20.05	22.01	0.24	**25.27**
18:00	2049	28.62	46.63	**56.60**	45.26
19:00	4312.62	24.32	51.25	**54.32**	53.35
20:00	1431.83	30.65	52.75	**55.53**	52.97
21:00	6212.99	19.18	56.36	**61.62**	54.24
22:00	184.62	68.81	72.80	**75.06**	72.36
23:00	103.45	59.85	61.25	58.22	**61.90**
Avg. (24 h)	1534.02	28.36	30.80	28.55	**31.30**
Avg. (off-peak)	93.08	**41.56**	35.54	36.69	35.72
Avg. (peak)	2254.49	21.76	28.44	24.48	**29.08**

Table 3: Out of sample variance-Illinois Hub

Hour	$\sigma^2_{Unhedged}$	Naïve (%)	MV (%)	ARDL (1,1) (%)	GARCH (1,1) (%)
0:00	334.6	**58.91**	52.23	51.75	50.30
1:00	357.89	60.46	59.97	60.39	**60.80**
2:00	260.64	**57.31**	42.45	45.23	35.93
3:00	257.25	**60.38**	55.29	58.06	55.66
4:00	348.16	**46.34**	33.19	39.77	31.09
5:00	542.88	**46.50**	21.80	33.78	21.85
6:00	2098.88	**10.51**	−1.14	0.74	−2.44
7:00	3940.42	**1.50**	−52.76	−97.51	−41.18
8:00	1049.87	5.76	12.51	**17.07**	14.42
9:00	1008.18	**42.42**	41.31	40.92	40.57
10:00	4469.84	28.26	51.65	**52.46**	51.94
11:00	2111.35	39.32	52.17	55.52	**57.13**
12:00	4184.7	30.90	33.55	**35.33**	25.71
13:00	1741.09	**28.15**	3.40	−1.84	24.32
14:00	1228.2	**28.35**	22.07	18.85	24.71
15:00	1946.15	**22.37**	13.20	−2.58	20.40
16:00	2309.48	24.11	21.26	13.31	**28.45**
17:00	1940.1	**19.09**	8.65	9.36	9.12
18:00	918.7	**14.56**	10.50	13.72	10.92
19:00	1964.45	23.23	17.93	**24.28**	16.47
20:00	928.62	16.76	−0.34	15.38	**16.99**
21:00	2774.2	32.81	46.10	41.01	**46.92**
22:00	494.9	**60.55**	45.37	51.98	51.40
23:00	197.64	**46.42**	22.98	26.86	26.20
Avg. (24 h)	1558.67	**33.54**	25.56	25.16	28.24
Avg. (off-peak)	349.25	**54.61**	41.66	45.98	41.65
Avg. (peak)	2163.39	**23.01**	17.50	14.75	21.53

Table 4: Out of sample variance-Indiana Hub

Hour	$\sigma^2_{Unhedged}$	Naïve (%)	MV (%)	ARDL (1,1) (%)	GARCH (1,1) (%)
0:00	126.02	**40.22**	24.59	20.48	21.37
1:00	165.12	**36.27**	8.25	−3.89	0.85
2:00	147.36	**43.53**	24.97	28.01	23.85
3:00	174.38	**61.30**	46.29	40.57	44.74
4:00	335.58	**35.40**	19.49	13.80	20.99
5:00	849.75	**25.25**	10.82	16.32	16.22
6:00	2856.02	**11.62**	−8.55	−11.81	−2.22
7:00	7221.02	**3.40**	−49.39	−59.34	−44.59
8:00	987.35	**14.59**	8.48	12.56	8.94
9:00	633.19	**25.27**	10.97	9.97	17.49
10:00	2591.32	26.86	**30.73**	21.00	27.57
11:00	1329.13	**27.62**	17.03	22.85	16.54
12:00	4090.04	**15.38**	−47.25	−20.84	−55.67
13:00	2536.24	**18.30**	8.09	15.07	12.50
14:00	1718.51	**18.10**	11.99	−4.23	17.49
15:00	5627	**10.13**	−3.28	−2.18	−21.93
16:00	6169.63	**8.15**	3.39	−13.62	−12.84
17:00	1869.24	**6.23**	−2.13	−8.71	3.14
18:00	869.02	**19.38**	2.23	7.67	−9.87
19:00	2276.05	**14.01**	6.82	10.93	7.98
20:00	1070.45	**18.28**	6.36	4.10	13.57
21:00	2226.36	23.05	**31.81**	23.22	31.19
22:00	208.67	**−1.08**	−47.75	−14.64	−19.46
23:00	156.87	**33.82**	25.12	23.64	25.59
Avg. (24 h)	1926.43	**22.30**	5.79	5.45	5.98
Avg. (off-peak)	270.47	**34.34**	13.97	15.54	16.77
Avg. (peak)	2754.41	**16.27**	1.71	0.41	0.58

ranges between 40.20% and 44.34% on the Texas hub. The only other hub to have an average variance reduction >40% for any technique is Minnesota (naïve). Overall, these findings are consistent with the lack of hedging effectiveness reported by Bystrom (2003), Hanly et al. (2017), and Boroumand et al. (2019) and Pena (2023).

Table 5: Out of sample variance-Louisiana Hub

Hour	$\sigma^2_{Unhedged}$	Naïve (%)	MV (%)	ARDL (1,1) (%)	GARCH (1,1) (%)
0:00	41.74	34.91	**35.36**	23.65	34.16
1:00	230.64	**2.92**	2.02	−21.45	−0.15
2:00	306.17	**5.26**	−2.51	−39.54	−3.68
3:00	303.19	**6.58**	3.81	−7.49	3.92
4:00	91.53	**26.76**	8.55	10.23	11.19
5:00	137.97	**12.72**	−0.93	1.86	−1.38
6:00	1623.37	**5.30**	−38.15	−55.57	−31.46
7:00	4111.44	**2.91**	−22.52	−37.78	−31.15
8:00	414.6	−11.11	6.75	−6.26	**7.22**
9:00	612.29	31.33	33.56	34.01	**38.93**
10:00	3196.01	19.04	19.61	21.23	**23.75**
11:00	3457.63	**0.66**	−14.32	−15.86	−8.40
12:00	6695.69	**1.45**	−4.85	−6.35	−0.66
13:00	10909.61	**0.19**	−6.18	−3.79	−1.72
14:00	2479.8	**3.43**	−1.77	0.21	−2.76
15:00	7870.03	**3.99**	−9.49	−18.79	−13.17
16:00	2919.91	**6.02**	−16.47	−25.35	−16.34
17:00	1653.79	**3.27**	−16.32	−32.10	−6.95
18:00	1143.02	16.61	12.04	**22.67**	12.94
19:00	3304.59	**13.61**	9.58	10.04	12.81
20:00	1469.69	**5.76**	−0.23	3.71	−0.09
21:00	2749.85	36.26	49.94	**63.78**	50.03
22:00	444.33	**−4.18**	−28.55	−21.48	−23.04
23:00	79.67	−25.73	**1.19**	−9.09	−7.31
Avg. (24 h)	2343.61	**8.25**	0.84	−4.56	1.95
Avg. (off-peak)	204.41	**7.40**	2.37	−7.91	1.72
Avg. (peak)	3413.21	**8.67**	0.08	−2.89	2.06

Table 6: Out of sample variance-Michigan Hub

Hour	$\sigma^2_{Unhedged}$	Naïve (%)	MV (%)	ARDL (1,1) (%)	GARCH (1,1) (%)
0:00	200.90	**29.57**	11.76	13.91	13.70
1:00	169.40	**38.81**	18.87	20.81	16.58
2:00	228.30	**18.23**	−12.51	−3.99	−0.97
3:00	166.99	**48.44**	28.56	32.61	27.56
4:00	394.35	**20.32**	−0.06	−0.34	1.44
5:00	491.73	**27.38**	16.08	16.94	23.37
6:00	2413.34	**10.21**	−11.52	−22.53	−6.31
7:00	5185.95	**4.73**	−44.37	−93.11	−37.77
8:00	937.42	**14.53**	6.70	7.64	10.11
9:00	715.10	**34.41**	28.40	13.22	30.22
10:00	3145.86	25.61	31.59	36.95	**38.59**
11:00	1369.73	30.23	31.32	30.88	**31.46**
12:00	2969.51	**26.72**	14.22	19.97	1.87
13:00	2158.97	**25.34**	−3.96	1.15	−0.42
14:00	1395.95	**26.10**	5.65	1.20	5.98
15:00	4843.34	**14.71**	−11.39	−17.20	−11.39
16:00	5531.77	**12.84**	3.61	−15.07	−2.17
17:00	2060.19	**19.09**	1.96	0.54	2.19
18:00	574.98	−13.34	−10.33	−16.83	**−5.68**
19:00	1870.69	**7.92**	−3.92	0.98	−7.95
20:00	949.75	**−5.23**	−6.86	−20.42	−7.57
21:00	2219.18	22.32	32.81	29.92	**35.06**
22:00	203.97	**23.27**	−5.03	−7.22	4.37
23:00	225.71	**12.61**	−10.28	−3.28	−7.16
Avg. (24 h)	1684.29	**19.78**	4.64	1.11	6.46
Avg. (off-peak)	260.17	**27.33**	5.92	8.68	9.86
Avg. (peak)	2396.36	**16.01**	3.99	−2.67	4.76

The Table 2 shows the out-of-sample percentage variance reduction of dollar returns (as compared to an unhedged position) for 1-week hedged portfolios on the Arkansas hub. MV, ARDL(1,1), and GARCH(1,1) hedge ratios are calculated using an 8-week estimation period. A rolling window approach is then used to update the MV, ARDL (1,1) and GARCH (1,1)

Table 7: Out of sample variance-Minnesota Hub

Hour	$\sigma^2_{Unhedged}$	Naïve (%)	MV (%)	ARDL (1,1) (%)	GARCH (1,1) (%)
0:00	301.48	**39.15**	−7.89	7.84	−8.40
1:00	308.53	**57.01**	46.89	52.09	50.83
2:00	295.70	**61.36**	56.98	59.22	55.90
3:00	358.60	**60.38**	55.24	56.91	53.29
4:00	353.05	**38.47**	−2.15	−26.45	10.61
5:00	491.04	**65.41**	56.69	59.51	57.53
6:00	2022.22	**26.73**	7.67	1.54	9.96
7:00	3200.61	**4.51**	−304.16	−548.79	−357.79
8:00	1066.95	**32.94**	−28.18	−69.34	−35.28
9:00	1685.82	**61.38**	49.32	42.64	57.28
10:00	6287.70	44.62	67.15	**71.53**	68.29
11:00	2543.26	58.03	67.16	**72.95**	64.06
12:00	4729.13	43.15	52.65	**59.80**	56.71
13:00	1171.23	**53.26**	45.18	46.85	38.83
14:00	1542.98	**48.28**	30.93	26.19	24.07
15:00	995.07	49.33	50.73	**51.85**	47.55
16:00	1056.70	**36.46**	22.03	27.63	22.21
17:00	1747.94	**39.27**	30.76	36.81	34.29
18:00	1078.15	**38.39**	24.39	27.54	28.21
19:00	2496.94	**40.15**	27.62	26.79	25.74
20:00	1687.77	**44.75**	33.53	35.21	34.20
21:00	4061.54	34.10	45.42	**46.04**	43.90
22:00	475.82	15.96	−35.95	**17.06**	−39.19
23:00	319.89	**38.37**	17.22	34.16	28.81
Avg. (24 h)	1678.26	**42.98**	17.05	8.98	15.48
Avg. (off-peak)	363.01	**47.01**	23.38	32.54	26.17
Avg. (peak)	2335.88	**40.96**	13.89	−2.80	10.14

Table 8: Out of sample variance-Mississippi Hub

Hour	$\sigma^2_{Unhedged}$	Naïve (%)	MV (%)	ARDL (1,1) (%)	GARCH (1,1) (%)
0:00	42.10	33.05	**41.72**	37.00	37.95
1:00	40.91	29.40	33.90	39.30	**41.83**
2:00	66.80	9.52	8.69	2.72	**11.21**
3:00	61.45	15.68	27.09	27.70	**29.28**
4:00	93.75	17.36	13.92	12.64	**19.73**
5:00	123.00	−2.99	0.24	**1.60**	−0.76
6:00	1520.77	**5.90**	−42.89	−63.83	−35.99
7:00	4332.15	**4.50**	−17.10	−27.95	−20.19
8:00	293.52	0.09	**24.79**	23.15	18.62
9:00	437.50	**56.19**	22.48	33.99	33.41
10:00	1829.18	31.89	32.98	**33.47**	30.77
11:00	569.01	**25.89**	7.03	3.44	−5.10
12:00	2406.28	**17.42**	8.13	9.10	7.56
13:00	1291.80	**10.45**	6.63	10.29	6.45
14:00	1609.09	**23.98**	−0.68	14.68	5.29
15:00	4626.03	**9.87**	−7.46	−2.94	−8.88
16:00	3271.50	**13.94**	8.93	−2.92	2.17
17:00	1444.68	**17.48**	3.41	4.64	12.73
18:00	884.15	31.68	34.02	**39.21**	28.77
19:00	2269.32	**42.59**	32.47	28.92	23.22
20:00	606.39	−0.69	−2.55	−19.72	**9.41**
21:00	3085.54	62.23	56.17	**70.52**	57.16
22:00	105.50	−152.64	−236.49	−99.39	**−84.78**
23:00	70.37	−115.95	**10.72**	−91.42	−4.87
Avg. (24 h)	1295.03	7.79	2.76	3.51	**8.96**
Avg. (off-peak)	75.49	−20.82	−12.52	−8.73	**6.20**
Avg. (peak)	1904.81	**22.09**	10.40	9.63	10.34

hedge ratios each week. The best performer for each hour is highlighted in bold.

The Table 3 shows the out-of-sample percentage variance reduction of dollar returns (as compared to an unhedged position)

Table 9: Out of sample variance-Texas Hub

Hour	$\sigma^2_{Unhedged}$	Naïve (%)	MV (%)	ARDL (1,1) (%)	GARCH (1,1) (%)
0:00	306.40	41.22	52.86	**54.64**	52.16
1:00	535.46	33.06	57.12	**59.04**	57.16
2:00	542.86	27.68	46.95	**48.54**	47.49
3:00	506.57	29.24	51.96	**54.06**	51.41
4:00	488.03	34.21	51.71	**55.80**	52.03
5:00	688.05	39.79	55.70	**59.34**	55.81
6:00	2337.87	**34.80**	17.18	14.08	20.19
7:00	4140.07	**20.57**	−127.09	−140.28	−62.06
8:00	2076.98	**69.33**	47.83	65.36	27.96
9:00	5494.59	49.81	60.76	60.81	**63.63**
10:00	11707.41	34.28	61.84	56.19	**62.84**
11:00	4882.56	38.95	68.11	**71.95**	63.99
12:00	11458.66	**24.21**	−88.31	−71.11	−63.10
13:00	5156.81	34.98	37.44	35.25	**39.80**
14:00	6367.13	30.55	52.25	**53.94**	53.11
15:00	5895.24	**21.73**	11.24	12.91	11.55
16:00	3022.77	**31.21**	31.12	13.30	25.86
17:00	4610.39	42.75	**59.93**	14.87	58.43
18:00	4963.05	52.24	65.43	**69.50**	56.88
19:00	9554.48	42.63	64.37	66.49	**66.58**
20:00	4567.58	49.23	76.66	**79.50**	77.40
21:00	12375.31	30.20	62.47	**73.70**	62.66
22:00	1141.02	68.50	**90.14**	88.78	90.13
23:00	565.20	83.80	90.77	92.18	**92.18**
Avg. (24 h)	4307.69	40.21	41.60	41.20	**44.34**
Avg. (off-peak)	596.70	44.69	62.15	**64.05**	62.30
Avg. (peak)	6163.18	**37.97**	31.32	29.78	35.36

for 1-week hedged portfolios on the Illinois hub. MV, ARDL(1,1), and GARCH(1,1) hedge ratios are calculated using an 8-week estimation period. A rolling window approach is then used to update the MV, ARDL (1,1) and GARCH (1,1) hedge ratios each week. The best performer for each hour is highlighted in bold.

The Table 4 shows the out-of-sample percentage variance reduction of dollar returns (as compared to an unhedged position) for 1-week hedged portfolios on the Indiana hub. MV, ARDL(1,1), and GARCH(1,1) hedge ratios are calculated using an 8-week estimation period. A rolling window approach is then used to update the MV, ARDL (1,1) and GARCH (1,1) hedge ratios each week. The best performer for each hour is highlighted in bold.

The Table 5 shows the out-of-sample percentage variance reduction of dollar returns (as compared to an unhedged position) for 1-week hedged portfolios on the Louisiana hub. MV, ARDL(1,1), and GARCH(1,1) hedge ratios are calculated using an 8-week estimation period. A rolling window approach is then used to update the MV, ARDL (1,1) and GARCH (1,1) hedge ratios each week. The best performer for each hour is highlighted in bold.

The Table 6 shows the out-of-sample percentage variance reduction of dollar returns (as compared to an unhedged position) for 1-week hedged portfolios on the Michigan hub. MV, ARDL(1,1), and GARCH(1,1) hedge ratios are calculated using an 8-week estimation period. A rolling window approach is then used to update the MV, ARDL (1,1) and GARCH (1,1) hedge ratios each week. The best performer for each hour is highlighted in bold.

The Table 7 shows the out-of-sample percentage variance reduction of dollar returns (as compared to an unhedged position) for 1-week hedged portfolios on the Minnesota hub. MV, ARDL(1,1), and GARCH(1,1) hedge ratios are calculated using an 8-week estimation period. A rolling window approach is then used to update the MV, ARDL (1,1) and GARCH (1,1) hedge ratios each week. The best performer for each hour is highlighted in bold.

The Table 8 shows the out-of-sample percentage variance reduction of dollar returns (as compared to an unhedged position) for 1-week hedged portfolios on the Mississippi hub. MV, ARDL(1,1), and GARCH(1,1) hedge ratios are calculated using an 8-week estimation period. A rolling window approach is then used to update the MV, ARDL (1,1) and GARCH (1,1) hedge ratios each week. The best performer for each hour is highlighted in bold.

The Table 9 shows the out-of-sample percentage variance reduction of dollar returns (as compared to an unhedged position) for 1-week hedged portfolios on the Texas hub. MV, ARDL(1,1), and GARCH(1,1) hedge ratios are calculated using an 8-week estimation period. A rolling window approach is then used to update the MV, ARDL (1,1) and GARCH (1,1) hedge ratios each week. The best performer for each hour is highlighted in bold.

The frequency in which hedging leads to more risk as compared to the unhedged position is striking. 20.57% (158/768) of the 1-week hedged portfolios have a variance greater than their respective unhedged spot return series. This phenomenon is not evenly distributed across the MISO footprint as 64.56% (102/158) occur on three hubs: Louisiana (45), Michigan (33) and Mississippi

(24). Risk management seems to be especially challenging in Louisiana and Mississippi given this concentration and the fact the 24-h average variance reduction was less than 10% for each technique on both hubs.

Unsurprisingly, hedged portfolios that increase risk are more prevalent during peak demand hours. Of the 512 hedged portfolios employed during peak hours (6:00 EST-21:00 EST), 113 (22.07%) have a variance larger than the return series they are intended to hedge. 17.58% (45/256) of the hedged portfolios created during off-peak hours have a variance larger than the unhedged position. Each hedging strategy tends to be less effective during peak demand hours, which could be the result of intense hedging pressure creating a disconnect between real-time and day-ahead prices as described in Bonaldo et al. (2022).

While none of the hedging strategies consistently meet the 80% variance reduction benchmark, there are noticeable intraday and intra-hub differences in effectiveness. When comparing each technique across all 192 hourly time series, the naïve strategy most often ranks first in reducing risk. The naïve method was the top performer for 63.02% (121/192) of the hourly time series across MISO, followed by ARDL(1,1) (17.19%), GARCH(1,1) (13.02%), and MV (6.77%). While the naïve and ARDL (1,1) models are much more likely to finish first as compared to MV and GARCH (1,1), they also are more likely to rank last. ARDL(1,1) is the worst performer 33.33% of the time, followed by naïve (26.04%), MV (21.35%) and GARCH(1,1) (19.27%).

Tables 10-12 provide the average variance reduction obtained per technique for the following three clusters, respectively: 24 h, peak demand hours, and off-peak demand hours. Table 10 reveals the naïve strategy produces the largest 24-h average variance reduction across the MISO footprint (25.40%) and is the most effective in reducing risk on 5 of the 8 MISO hubs (IL, IN, LA, MI, MN) over a 24-h period. The ARDL (1,1) model is the least effective risk management technique over a 24-h timeframe with an average reduction in variance of 13.68%. Tables 11 and 12 reveal a similar pattern during the peak and off-peak hours. The naïve approach results in the greatest average reduction in variance during peak (23.34%) and off-peak (29.52%) hours across the exchange. The ARDL (1,1) model is least effective risk management tool during peak hours, while MV hedging results in the lowest average variance reduction during off-peak hours.

The following Table 10 shows the 24-h average variance reduction associated with each hedging strategy on the exchange.

The following Table 11 shows the average variance reduction associated with each hedging strategy during peak hours (6:00 EST-21:00 EST) on the exchange.

The following Table 12 shows the average variance reduction associated with each hedging strategy during off-peak hours (22:00 EST-23:00 EST, 0:00 EST-5:00 EST) on the exchange.

When first established, MISO covered several midwestern states and Manitoba. MISO's footprint has recently extended to the southern United States. The factors of generation vary between the northern and southern hubs. For instance, coal plays a much larger role in power generation in the northern hubs, while wind and natural gas generation are more prevalent in the southern zones. These production differences may create discrepancies in the ability to effectively hedge between the two regions. Table 13 is a revisualization of the information shown in Tables 10-12 to assess this possibility. The naïve strategy is clearly the best performer in the 4 northern hubs (IL, IN, MI, MN) as it has the highest average variance reduction during peak hours, off-peak hours, and across the entire day. This is not the case for the southern hubs (AR, LA, MS, TX). While the naïve approach provides the largest variance reduction during peak hours, GARCH(1,1) is the best risk management tool during off-peak hours and throughout the day in the southern region. Table 13 also reveals that for all 3 timeframe clusters, the best hedging strategy for the northern hubs is more effective than the top performer in the southern hubs.

Table 10: Variance reduction by hedging strategy-24 h

Hub	Naïve (%)	MV (%)	ARDL (%)	GARCH (%)
AR	28.36	30.80	28.55	31.30
IL	33.54	25.56	25.16	28.24
IN	22.30	5.79	5.45	5.98
LA	8.25	0.84	−4.56	1.95
MI	19.78	4.64	1.11	6.46
MN	42.98	17.05	8.98	15.48
MS	7.79	2.76	3.51	8.96
TX	40.21	41.60	41.20	44.34
Average (all hubs)	25.40	16.13	13.68	17.84

Table 11: Variance reduction by hedging strategy-peak hours

Hub	Naïve (%)	MV (%)	ARDL (%)	GARCH (%)
AR	21.76%	28.44%	24.48%	29.08%
IL	23.01	17.50	14.75	21.53
IN	16.27	1.71	0.41	0.58
LA	8.67	0.08	−2.89	2.06
MI	16.01	3.99	−2.67	4.76
MN	40.96	13.89	−2.80	10.14
MS	22.09	10.40	9.63	10.34
TX	37.97	31.32	29.78	35.36
Average (all hubs)	23.34	13.42	8.84	14.23

Table 12: Variance reduction by hedging strategy-off peak hours

Hub	Naïve (%)	MV (%)	ARDL (%)	GARCH (%)
AR	41.56	35.54	36.69	35.72
IL	54.61%	41.66	45.98	41.65
IN	34.34	13.97	15.54	16.77
LA	7.40	2.37	−7.91	1.72
MI	27.33	5.92	8.68	9.86
MN	47.01	23.38	32.54	26.17
MS	−20.82	−12.52	−8.73	6.20
TX	44.69	62.15	64.05	62.30
Average (all hubs)	29.52	21.56	23.35	25.05

Table 13: Hedging performance-northern and southern Hubs

Panel A: 24 h-Northern Hubs				
Hub		**MV (%)**	**ARDL (%)**	**GARCH (%)**
IL	33.54	25.56	25.16	28.24
IN	22.30	5.79	5.45	5.98
MI	19.78	4.64	1.11	6.46
MN	42.98%	17.05	8.98	15.48
Average	**29.65**	13.26	10.18	14.04

Panel B: 24 h-Southern Hubs				
Hub	**Naïve (%)**	**MV (%)**	**ARDL (%)**	**GARCH (%)**
AR	28.36	30.80	28.55	31.30
LA	8.25	0.84	−4.56	1.95
MS	7.79	2.76	3.51	8.96
TX	40.21	41.60	41.20	44.34
Average	21.15	19.00	17.18	**21.63**

Panel C: On Peak-Northern Hubs				
Hub	**Naïve (%)**	**MV (%)**	**ARDL (%)**	**GARC (%) H**
IL	23.01	17.50	14.75	21.53
IN	16.27	1.71	0.41	0.58
MI	16.01	3.99	−2.67	4.76
MN	40.96	13.89	−2.80	10.14
Average	**24.06**	9.27	2.42	9.25

Panel D: On-Peak Southern Hubs				
Hub	**Naïve (%)**	**MV (%)**	**ARDL (%)**	**GARCH (%)**
AR	21.76	28.44	24.48	29.08
LA	8.67	0.08	−2.89	2.06
MS	22.09	10.40	9.63	10.34
TX	37.97	31.32	29.78	35.36
Average	**22.62**	17.56	15.25	19.21

Panel E: Off Peak-Northern Hubs				
Hub	**Naïve (%)**	**MV (%)**	**ARDL (%)**	**GARCH (%)**
IL	54.61	41.66	45.98	41.65
IN	34.34	13.97	15.54	16.77
MI	27.33	5.92	8.68	9.86
MN	47.01	23.38	32.54	26.17
Average	40.82	21.23	25.68	23.61

Panel F: Off-Peak Southern Hubs				
Hub	**Naïve (%)**	**MV (%)**	**ARDL (%)**	**GARCH (%)**
AR	41.56	35.54	36.69	35.72
LA	7.40	2.37	−7.91	1.72
MS	−20.82	−12.52	−8.73	6.20
TX	44.69	62.15	64.05	62.30
Average	18.21	21.88	21.02	26.48

The following Table 13 summarizes the average variance reduction obtained with each hedging strategy based on geographic region. The technique that produces the greatest risk reduction is shown in bold.

5. CONCLUSION

The purpose of this study is to provide an in-depth analysis of hedging effectiveness on the largest wholesale electricity market in North America. The short-term (1-week) out- of-sample performance of four hedging techniques (naïve, minimum variance, ARDL(1,1), and GARCH(1,1)) is evaluated for 24 hourly time series on each of MISO's eight regional hubs. An 8-week rolling windows estimation technique is used to update the minimum variance, ARDL(1,1) and GARCH(1,1) hedge ratio estimates throughout the sample. Consistent with prior research covering European markets, none of the hedging strategies can be classified as highly effective, and several of the hedged portfolios have a variance larger than the spot price return series they are designed to hedge. While none of the hedging strategies are highly effective, the naïve approach is the best of the four risk reduction strategies in the northern hubs, while naïve and GARCH(1,1) are the top performers in the southern hubs. Hedging seems to be more effective overall on the older, northern hubs, which could be a function of the differences in generation sources used in the two regions.

The inability to store wholesale power is likely a major factor in the relative ineffectiveness of hedging electricity as compared to other commodities. Since electricity cannot be efficiently stored, real-time and day-ahead prices exhibit large price spikes, seasonalities, and may fall below zero during times of high congestion and/or low demand. These unique properties accentuate the need for effective risk mitigation tools in wholesale electricity markets. Risk management efforts in wholesale electricity markets is further hindered by noncompetitive market participants and asymmetric information as identified by Hesamzadeh et al. (2020). While all wholesale power market participants would benefit from advancements in risk management, electricity retailers—who typically do not own generation capacity and oftentimes have limited short-term control over their revenue structure—are perhaps in the greatest need of effective hedging strategies.

The challenges that practitioners and academicians face in hedging wholesale power are likely to expand as the world continues to shift from non-renewable to renewable forms of generation. The transition from fossil fuels (coal, natural gas) to wind and solar power equates to a greater reliance on non-storable factors of production. Market participants are increasingly being faced with hedging concerns on two fronts: power generation and delivery. Future research should focus on these challenges to identify effective hedging strategies as we continue to transition to more environmentally friendly power generation methods.

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