

Energy Efficiency and Environmental Benefits of Waste Heat Recovery Technologies in Fishmeal Production Plants: A Case Study in Vietnam

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S1. The data collected from the field

Table S1.1. Fish meal production output at the KHS plant from 2016 to 2022 (unit: tons)

Month	2016	2017	2018	2019	2020	2021	2022
Jan	464	488	775	853	895	761	940
Feb	149	157	244	587	616	345	389
Mar	445	468	238	262	275	421	472
Apr	454	478	761	837	879	747	923
May	504	531	1,112	1223	1284	890	1349
Jun	447	470	268	569	597	575	564
Jul	470	495	1,056	1162	1104	938	1159
Aug	390	410	1,315	1447	1374	943	1443
Sep	492	518	1,342	1476	1402	915	1473
Oct	342	360	766	843	800	680	840
Nov	226	238	910	1001	951	808	998
Dec	255	268	996	1096	1041	885	895
<i>Mean</i>	<i>386.5</i>	<i>406.8</i>	<i>815.3</i>	<i>946.3</i>	<i>934.8</i>	<i>742.3</i>	<i>953.8</i>
Total	4,638	4,881	9,783	11,356	11,218	8,908	11,445

Table S2.2. Electricity consumption at the KHS plant from 2016 to 2022 (unit: kWh)

Month	2016	2017	2018	2019	2020	2021	2022
Jan	40,660	42,800	72,258	75,510	73,244	67,495	71,047
Feb	17,955	18,900	9,677	10,112	9,809	15,375	9,515
Mar	48,545	51,100	4,516	4,719	4,578	14,281	4,440
Apr	57,855	60,900	70,968	74,162	71,937	66,290	69,779
May	65,835	69,300	83,871	87,645	85,016	78,342	82,465
Jun	70,395	74,100	19,355	20,226	19,619	18,079	19,031
Jul	70,490	74,200	5,839	47,902	45,986	45,434	47,825
Aug	69,350	73,000	32,258	33,710	32,361	31,973	33,656
Sep	68,020	71,600	194,839	203,607	195,462	112,768	198,786
Oct	48,420	50,968	132,258	138,210	132,681	86,975	85,972
Nov	52,097	54,839	115,484	120,681	115,854	98,765	120,488
Dec	42,902	45,160	101,224	105,779	101,548	91,082	95,876
<i>Mean</i>	<i>54,377.0</i>	<i>57,238.9</i>	<i>70,212.3</i>	<i>76,855.3</i>	<i>74,007.9</i>	<i>60,571.6</i>	<i>69,906.7</i>
Total	652,524	686,867	842,547	922,263	888,095	726,859	838,880

Table S1.3. Rice husk pellet consumption at the KHS plant from 2016 to 2022 (unit: tons)

Month	2016	2017	2018	2019	2020	2021	2022
Jan	258	272	264	251	263	284	271
Feb	528	556	407	387	406	438	418
Mar	581	612	365	347	364	393	374
Apr	521	548	595	565	594	641	610
May	697	734	521	495	520	561	535
Jun	685	721	549	522	548	591	563
Jul	528	556	423	402	422	456	434
Aug	450	474	399	379	398	430	409
Sep	665	700	307	292	306	331	315
Oct	295	310	494	469	493	532	507
Nov	347	365	565	537	564	609	580
Dec	522	549	591	561	590	637	606
Mean	506.4	533.1	456.7	433.9	455.7	491.9	468.5
Total	6,077	6,397	5,480	5,207	5,468	5,903	5,622

S2. Secondary data

Table S2.1. Wholesale electricity price framework of EVN from 2016 to 2022

Electricity Tariff (KWh)	2016 [1]	2017 [2]	2018 [3]	2019 [4]	2020 [5]	2021 [6]	2022 [7]
0 -50	1.484	1.583	1.549	1.678	1.687	1.678	1.678
51 - 100	1.533	1.635	1.600	1.734	1.734	1.734	1.734
101 – 200	1.786	1.893	1.858	2.014	2.014	2.014	2.014
201-300	2.242	2.374	2.340	2.536	2.629	2.536	2.536
301-400	2.503	2.650	2.615	2.834	2.834	2.834	2.834
> 400	2.587	2.736	2.701	2.927	2.983	2.961	2.927

Conversion factor:

- 1 kWh = 3.6×10^{-3} GJ = 3.6×10^{-6} (TJ) [8]
- 1 kg of RHPC = 14.63×10^{-3} (GJ) = 14.63×10^{-6} (TJ) [9]
- 1 ton of RHPC generates 16,100 MJ/ton \rightarrow 0.1 kg CO₂/MJ \rightarrow 100,000 kg CO₂/TJ [10]

The percentage of heat lost through flue gas: %*fg* = 18 [11].

The efficiency of the heat recovery system: %*HR* = 30 [11].

S3. Computational data

Table S3.1. Total energy consumption at the KHS plant from 2016 to 2022 (unit: GJ)

Month	2016	2017	2018	2019	2020	2021	2022
Jan	3,926.77	4,133.44	4,122.45	3,941.04	4,116.34	4,403.86	4,218.51
Feb	7,792.20	8,202.32	5,989.25	5,693.09	5,974.84	6,470.04	6,143.48
Mar	8,680.64	9,137.52	5,356.21	5,089.94	5,343.08	5,804.14	5,494.77
Apr	7,824.66	8,236.48	8,960.33	8,536.59	8,942.06	9,616.38	9,182.38
May	10,438.51	10,987.90	7,924.17	7,556.64	7,909.23	8,493.46	8,117.28
Jun	10,274.24	10,814.99	8,101.55	7,703.09	8,082.42	8,717.82	8,309.21
Jul	7,981.33	8,401.40	6,209.51	6,051.51	6,338.57	6,830.42	6,521.56
Aug	6,837.55	7,197.42	5,953.50	5,666.86	5,939.28	6,403.70	6,110.30
Sep	9,973.82	10,498.76	5,192.83	4,999.82	5,183.85	5,244.56	5,323.82
Oct	4,482.85	4,718.78	7,703.35	7,363.41	7,686.80	8,098.99	7,724.63
Nov	5,260.50	5,537.37	8,681.69	8,287.10	8,662.36	9,260.46	8,914.62
Dec	7,784.72	8,194.44	9,010.74	8,594.82	8,990.29	9,642.59	9,216.29
Mean	7,604.8	7,969.0	6,933.8	6,623.7	6,930.8	7,415.5	7,106.4
Total	91,258	87,659	83,206	79,484	83,169	88,986	85,277

Note:

In this study, TEC refers to the total energy consumption during the operation of the KHS factory, encompassing two sources: electricity and rice husk pellets. The TEC is computed as the sum of electricity consumption (EC) and rice husk pellet consumption (RHPC) using Equation 1.

$$TEC = EC + RHPC \text{ (Equation 1)}$$

Where: TEC represents the total energy consumption measured in gigajoules (GJ); EC denotes the electricity consumption by the KHS factory (Table S2.2); RHPC signifies the amount of rice husk pellets consumed by the factory (Table S2.3).

To facilitate the analysis, the unit of EC is converted from kilowatt-hours (kWh) to gigajoules (GJ) using the conversion factor of $1 \text{ kWh} = 3.6 \times 10^{-3} \text{ GJ}$ [8].

Similarly, the unit of RHPC is converted from tons to gigajoules (GJ) using the conversion factor: $1 \text{ kg of RHPC} = 3,500 \times 4.18 \times 10^{-6} \text{ GJ}$ [9].

Table S3.2. The specific energy consumption (SEC) index at the KHS plant from 2016 to 2022 (unit: GJ/ton)

Month	2016	2017	2018	2019	2020	2021	2022
Jan	8.46	8.47	5.32	4.62	4.6	5.79	4.49
Feb	52.30	52.24	24.55	9.7	9.69	18.75	15.79
Mar	19.51	19.52	22.51	19.44	19.44	13.79	11.64
Apr	17.23	17.23	11.77	10.2	10.17	12.87	9.95
May	20.71	20.69	7.13	6.18	6.16	9.54	6.02
Jun	22.98	23.01	30.23	13.54	13.53	15.16	14.73
Jul	16.98	16.97	5.88	5.21	5.74	7.28	5.63
Aug	17.53	17.55	4.53	3.92	4.32	6.79	4.23
Sep	20.27	20.27	3.87	3.39	3.7	5.73	3.62
Oct	13.11	13.11	10.06	8.74	9.6	11.9	9.19
Nov	23.28	23.27	9.54	8.28	9.11	11.46	8.93
Dec	30.53	30.58	9.05	7.84	8.64	10.9	10.3
<i>Mean</i>	<i>21.9</i>	<i>21.9</i>	<i>12.0</i>	<i>8.4</i>	<i>8.7</i>	<i>10.8</i>	<i>8.7</i>

Note:

In this study, the specific energy consumption (SEC) refers to the amount of energy required to produce one ton of fish meal at the KHS plant. The SEC index at the KHS plant was calculated on a monthly basis and averaged over each year for a continuous period of seven years (2016-2022). It was determined by dividing the total energy consumed (TEC) by the fish meal output (FMO) according to Equation 2:

$$SEC = TEC/FMO \quad (2)$$

The unit used for SEC is GJ/ton, TEC is measured in GJ, and FMO is measured in tons.

Table S3.3. The annual energy savings from heat recovery

Index	2018	2019	2020	2021	2022
AEC (KWh)	842,547	922,263	888,095	726,859	838,880
CC(kWh-GJ)	$3.6*10^{-3}$	$3.6*10^{-3}$	$3.6*10^{-3}$	$3.6*10^{-3}$	$3.6*10^{-3}$
AEC (GJ)	3,033.17	3,320.15	3,197.14	2,616.69	3,019.97
ARHPC (ton)	5,480	5,207	5,468	5,903	5,622
CC _{kg RHPC-GJ}	$14.63*10^{-3}$	$14.63*10^{-3}$	$14.63*10^{-3}$	$14.63*10^{-3}$	$14.63*10^{-3}$
ARHPC (GJ)	80,172.40	76,178.41	79,996.84	86,360.89	82,249.86
%fg(%)	18%	18%	18%	18%	18%
%HR (%)	30%	30%	30%	30%	30%
AES_{EC} (GJ/year)	163.79	179.29	172.65	141.30	163.08
AES_{RHPC} (GJ/year)	4,329.31	4,113.63	4,319.83	4,663.49	4,441.49
TAES_{HR} (GJ/year)	4,493.10	4,292.92	4,492.48	4,804.79	4,604.57

Note:

- AEC (kWh): Annual electricity consumption at KHS plant (unit: kWh)
- CC_{kWh-GJ}: Conversion coefficient from kWh to GJ $\Leftrightarrow \text{kWh} = 3.6*10^{-3} \text{ GJ}$ [8]
- AEC (GJ): Annual electricity consumption at KHS plant (unit: GJ)
- **AEC (GJ) = AEC (kWh) * CC(kWh-GJ)**

- RHPC (ton): Rice husk pellet consumption at KHS (unit: tons)
- CC_{kg RHPC-GJ}: Conversion coefficient from mass of rice husk pallet consumption to GJ $\Leftrightarrow \text{Kg}_{\text{RHPC}} = 14.63*10^{-3} \text{ GJ}$ [9]
- ARHPC (ton): Annual rice husk pellet consumption at KHS plant (unit: ton)
- **ARHPC (GJ) = ARHPC (ton) * CC_(kg RHPC-GJ)**

- %fg is the percentage of heat lost through flue gas (%fg = 18) [11]
- %HR is the efficiency of the heat recovery system (%HR = 30) [11]
- AES_{EC} (GJ/year): The annual energy savings from electricity consumption (GJ/year)
- **AES_{EC} (GJ/year) = AEC(GJ) * %fg (%) * %HR (%)**

- AES_{RHPC} (GJ/year): The annual energy savings from rice husk pellet consumption (GJ/year)
- **AES_{RHPC} (GJ/year) = ARHPC (GJ) * %fg (%) * %HR (%)**

- TAES_{HR} (GJ/year): The total annual energy savings from heat recovery (GJ/year)
- **TAES_{HR} (GJ/year) = TAES_{EC} (GJ/year) + TAES_{RHPC} (GJ/year)**

Table S3.4. Calculation of Annual Energy Cost Savings at KHS Factory following the Installation of the Economization System (Unit: USD)

Index	2018	2019	2020	2021	2022	Mean
TAES _{EC} (GJ)	163.79	179.29	172.65	141.30	163.08	164.02
CC _{GJ-kWh}	277.78	277.78	277.78	277.78	277.78	277.78
P _{EC} (USD/kWh)	0.11	0.12	0.13	0.12	0.12	0.12
AECS_{EC} (USD)	5,161.30	6,122.45	6,008.51	4,881.21	5,568.91	5,548.48
TAES _{RHPC} (GJ)	4,329.31	4,113.63	4,319.83	4,663.49	4,441.49	4,373.55
CC _{GJ-RHP}	68.35	68.35	68.35	68.35	68.35	68.35
P _{RHPC} (USD/kgRHPC)	0.07	0.07	0.07	0.07	0.07	0.07
AECS_{RHPC} (USD)	20,714.34	19,682.38	20,668.98	22,313.28	21,251.08	20,926.01
TAECS (USD)	25,875.64	25,804.84	26,677.49	27,194.49	26,819.99	26,474.49

Note:

- TAES_{EC} (GJ): The total annual energy savings from electricity consumption (unit: GJ)
- CC_{GJ-kWh}: Conversion coefficient from GJ to kWh $\Leftrightarrow 1 \text{ GJ} = 10^3/3.6 \text{ kWh} = 277.78 \text{ kWh}$
- P_{EC} (USD/kWh): Price of electricity consumption in USD per kilowatt-hour (unit: USD)
- AECS_{EC} (USD): Annual energy cost savings from electricity consumption (unit: USD)
- **AECS_{EC} (USD) = TAES_E (GJ) * CC_{GJ-kWh} * P_{EC} (USD/kWh)**

- TAES_R (GJ): The total annual energy savings from rice husk pellet consumption (unit: GJ)
- CC_{GJ-RHPC}: Conversion coefficient from GJ to mass of rice husk pellet consumption $\Leftrightarrow 1 \text{ GJ} = 1 / (3,500 * 4.18 * 10^{-6}) \text{ kg of RHP} = 68.35 \text{ kg of RHPC}$
- P_{RHPC} (USD/kgRHPC): Price of one kg of rice husk pellet consumption (unit: USD/ kgRHPC)
- AECS_{RHPC} (USD): Energy cost savings from RHPC (rice husk pellet combustion) (unit: USD)
- **AECS_{RHPC} (USD) = TAES_R (GJ) * CC_{GJ-RHP} * P_{RHP} (USD/kgRHPC)**

- TAECs (USD): Total annual energy cost savings from energy consumption (unit: USD)
- **TAECs (USD) = AECS_{EC} (USD) + AECS_{RHPC} (USD)**

Table S3.5. CO₂ emissions to the environment resulting from operation of the KHS factory from 2016 - 2022

Index	2016	2017	2018	2019	2020	2021	2022
AEC (kWh)	652,524	686,867	842,547	922,263	888,095	726,859	838,880
CC _{kWh-TJ}	3.6*10 ⁻⁶	3.6*10 ⁻⁶	3.6*10 ⁻⁶	3.6*10 ⁻⁶	3.6*10 ⁻⁶	3.6*10 ⁻⁶	3.6*10 ⁻⁶
AEC (TJ)	2.35	2.47	3.03	3.32	3.20	2.62	3.02
ARHPC (ton)	6,077	6,397	5,480	5,207	5,468	5,903	5,622
CC _{kg RHPC-TJ}	14.63*10 ⁻³	14.63*10 ⁻³	14.63*10 ⁻³	14.63*10 ⁻³	14.63*10 ⁻³	14.63*10 ⁻³	14.63*10 ⁻³
ARHPC (TJ)	88.91	93.59	80.17	76.18	80.00	86.36	82.25
EF _{EC-CO₂}	253,611	253,611	253,611	253,611	253,611	253,611	253,611
CO₂(EC) (kg)	595,754	627,109	769,245	842,026	810,830	663,622	765,897
EF _{RHPC-CO₂}	100,000	100,000	100,000	100,000	100,000	100,000	100,000
CO₂ RHPC (kg)	8,890,651	9,358,811	8,017,240	7,617,841	7,999,684	8,636,089	8,224,986
CO₂ Total (kg)	9,486,405	9,985,920	8,786,485	8,459,867	8,810,514	9,299,711	8,990,883
AFMO (tons)	4,638	4,881	9,783	11,356	11,218	8,908	11,445
CO₂/FMO	2.05	2.05	0.90	0.74	0.79	1.04	0.79

Note:

- *AEC (kWh): Annual electricity consumption at KHS plant (unit: kWh)*
- *CC_{kWh-TJ}: Conversion coefficient from kWh to TJ $\Leftrightarrow kWh = 3.6*10^{-6}$ TJ*
- *AEC(TJ): Annual electricity consumption at KHS plant (unit: TJ)*
- ***EC(TJ) = AEC (kWh) * CC(kWh-TJ)***

- *ARHPC (ton): Annual rice husk pellet consumption at KHS (unit: tons)*
- *CC_{kg RHPC-TJ}: Conversion coefficient from mass of rice husk pellet consumption to TJ \Leftrightarrow
Kg_{RHPC} = 14.63*10⁻³ TJ*
- *ARHPC(TJ): Annual rice husk pellet consumption at KHS (unit: TJ)*
- ***ARHPC (TJ) = ARHPC (ton) * CC_(kg RHPC-TJ)***

- *EF_{EC-CO₂}: The default emission factor of CO₂ by electricity consumption \Leftrightarrow (kgCO₂/TJ) = 253,611 (KgCO₂/TJ) [12]*
- *EF_{RHPC-CO₂}: The default emission factor of CO₂ by RHPC \Leftrightarrow (kgCO₂/TJ) = 100,000 (kgCO₂/TJ) [10]*
- *CO₂(EC) (kg): CO₂ emissions to the environment resulting from electricity consumption (unit: kg)*
- ***CO₂(EC) (kg) = AEC(TJ) * EF_(EC-CO₂)***

- *CO₂(RHPC) (kg): CO₂ emissions to the environment resulting from rice husk pellets consumption (unit: kg)*
- ***CO₂(RHPC) (kg) = ARHPC (TJ) * EF_(RHPC-CO₂)***

- *FMO (tons): Fish meal output (unit: tons)*
- *CO₂/FMO: The percent of CO₂ emission per ton of FMO*
- ***CO₂/FMO = CO₂ (Total) (kg)/FMO (tons)***

S4. Data analysis and plotting in R software

4.1. QQ plots for the collected data from FMO, EC, and RHPC at the KHS factory

Create sample data

```
FMO <- c(464, 149, 445, 454, 504, 447, 470, 390, 492, 342, 226, 255, 488, 157, 468, 478, 531, 470, 495, 410, 518, 360, 238, 268, 775, 244, 238, 761, 1112, 268, 1056, 1315, 1342, 766, 910, 996, 853, 587, 262, 837, 1223, 569, 1162, 1447, 1476, 843, 1001, 1096, 895, 616, 275, 879, 1284, 597, 1104, 1374, 1402, 800, 951, 1041, 761, 345, 421, 747, 890, 575, 938, 943, 915, 680, 808, 885, 940, 389, 472, 923, 1349, 564, 1159, 1443, 1473, 840, 998, 895)
```

```
EC <- c(40660, 17955, 48545, 57855, 65835, 70395, 70490, 69350, 68020, 48420, 52097, 42902, 42800, 18900, 51100, 60900, 69300, 74100, 74200, 73000, 71600, 50968, 54839, 45160, 72258, 9677, 4516, 70968, 83871, 19355, 5839, 32258, 194839, 132258, 115484, 101224, 75510, 10112, 4719, 74162, 87645, 20226, 47902, 33710, 203607, 138210, 120681, 105779, 73244, 9809, 4578, 71937, 85016, 19619, 45986, 32361, 195462, 132681, 115854, 101548, 67495, 15375, 14281, 66290, 78342, 18079, 45434, 31973, 112768, 86975, 98765, 91082, 71047, 9515, 4440, 69779, 82465, 19031, 47825, 33656, 198786, 85972, 120488, 95876)
```

```
RHPC <- c(258, 528, 581, 521, 697, 685, 528, 450, 665, 295, 347, 522, 272, 556, 612, 548, 734, 721, 556, 474, 700, 310, 365, 549, 264, 407, 365, 595, 521, 549, 423, 399, 307, 494, 565, 591, 251, 387, 347, 565, 495, 522, 402, 379, 292, 469, 537, 561, 263, 406, 364, 594, 520, 548, 422, 398, 306, 493, 564, 590, 284, 438, 393, 641, 561, 591, 456, 430, 331, 532, 609, 637, 271, 418, 374, 610, 535, 563, 434, 409, 315, 507, 580, 606)
```

```
TEC <- c(3926.77, 7792.20, 8680.64, 7824.66, 10438.51, 10274.24, 7981.33, 6837.55, 9973.82, 4482.85, 5260.50, 7784.72, 4133.44, 8202.32, 9137.52, 8236.48, 10987.90, 10814.99, 8401.40, 7197.42, 10498.76, 4718.78, 5537.37, 8194.44, 4122.45, 5989.25, 5356.21, 8960.33, 7924.17, 8101.55, 6209.51, 5953.50, 5192.83, 7703.35, 8681.69, 9010.74, 3941.04, 5693.09, 5089.94, 8536.59, 7556.64, 7703.09, 6051.51, 5666.86, 4999.82, 7363.41, 8287.10, 8594.82, 4116.34, 5974.84, 5343.08, 8942.06, 7909.23, 8082.42, 6338.57, 5939.28, 5183.85, 7686.80, 8662.36, 8990.29, 4403.86, 6470.04, 5804.14, 9616.38, 8493.46, 8717.82, 6830.42, 6403.70, 5244.56, 8098.99, 9260.46, 9642.59, 4218.51, 6143.48, 5494.77, 9182.38, 8117.28, 8309.21, 6521.56, 6110.30, 5323.82, 7724.63, 8914.62, 9216.29)
```

```
SEC <- c(8.46, 52.3, 19.51, 17.23, 20.71, 22.98, 16.98, 17.53, 20.27, 13.11, 23.28, 30.53, 8.47, 52.24, 19.52, 17.23, 20.69, 23.01, 16.97, 17.55, 20.27, 13.11, 23.27, 30.58, 5.32, 24.55, 22.51, 11.77, 7.13, 30.23, 5.88, 4.53, 3.87, 10.06, 9.54, 9.05, 4.62, 9.7, 19.44, 10.2, 6.18, 13.54, 5.21, 3.92, 3.39, 8.74, 8.28, 7.84, 4.6, 9.69, 19.44, 10.17, 6.16, 13.53, 5.74, 4.32, 3.7, 9.6, 9.11, 8.64, 5.79, 18.75, 13.79, 12.87, 9.54, 15.16, 7.28, 6.79, 5.73, 11.9, 11.46, 10.9, 4.49, 15.79, 11.64, 9.95, 6.02, 14.73, 5.63, 4.23, 3.62, 9.19, 8.93, 10.3)
```

Plotting QQ plot for FMO data

```
qqnorm(FMO)
```

```
qqline(FMO)
```

Plotting QQ plot for EC data

```
qqnorm(EC)
```

```
qqline(EC)
```

```
# Plotting QQ plot for RHPC data
```

```
qqnorm(RHPC)
```

```
qqline(RHPC)
```

4.2. Multivariate correlation plots (FMO, EC, RHE, TEC, SEC) in R were generated using the `pairs.panels()` function from the `psych` package

```
# Load the psych library
```

```
library(psych)
```

```
# Combine data into a data frame
```

```
data <- data.frame(FMO, EC, RHE, TEC, SEC)
```

```
# Generate multivariate correlation plots
```

```
pairs.panels(data)
```

4.3. Analyzing the differences in the SEC index between the preceding years (2016 and 2017) and the subsequent years (2018, 2019, 2020, 2021, and 2022) during the installation of the economizer.

```
t.test(y2016,y2018)
```

```
t.test(y2016,y2019)
```

```
t.test(y2016,y2020)
```

```
t.test(y2016,y2021)
```

```
t.test(y2016,y2022)
```

```
t.test(y2017,y2018)
```

```
t.test(y2017,y2019)
```

```
t.test(y2017,y2020)
```

```
t.test(y2017,y2021)
```

```
t.test(y2017,y2022)
```

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