

ADVANCED FIRE-TUBE BOILER PROJECT

CONTENTS

ACKNOWLEDGMENT	1
PROJECT DESCRIPTION	3
INTRODUCTION	3
DISADVANTAGES OF EXISTING FIRE-TUBE BOILER DESIGN	4
SUMMARY OF PROJECT RESULTS	6
PERFORMANCE DATA	6
COMPARISON OF SEASONAL EFFICIENCIES	7

List of figures

FIGURE 1: THREE-PASS FIRE-TUBE STEAM BOILER	3
FIGURE 2: TWO-PASS REVERSE FLUE FIRE-TUBE HOT WATER BOILER	3
FIGURE 3: DEAD ZONE IN THREE-PASS BOILER	4
FIGURE 4: BOILER EFFICIENCY CURVES	4

List of tables

TABLE 1: SEASONAL INPUT/OUTPUT EFFICIENCY OF OLD INSTALLATION AT DEMO SITE	7
TABLE 2: SEASONAL INPUT/OUTPUT EFFICIENCY OF NEW INSTALLATION AT DEMO SITE	8

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Introduction

Fire-tube boilers are the most common heat generators used for production of hot water and steam ranging up to 25MW / 2500HP and 25 bar / 360 psi pressure. There are several families of boilers such as 2-pass reverse flue, 2-pass, 3-pass, and 4-pass and firebox, dryback and wetback design. The most common is the 3-pass design (in USA also called Scotch Marine design for it was initially used on ships and later adapted for use in stationary applications). All these families are basically very similar for they all have a round combustion chamber (also called the furnace), where combustion of fossil fuels takes place, and tubes (also called fire-, or smoke tubes). Behind the heat transfer wall is the boiler water that is heated up by energy released from combustion. In a steam boiler, the water turns to steam above the water line in the boiler and fills the steam space located at the top of the boiler, where it leaves through the steam valve. In hot water boiler there is no steam space at the top, so the entire boiler is filled with water. Some fire-tube boilers come with totally water cooled furnace while some designs have so called dry back, where the back of the furnace is not cooled, and is lined with refractory. Boiler door is not cooled in all fire-tube boilers and must therefore be lined with refractory material also. Mostly, in fire-tube boilers fossil fuels, gas and oil, are burnt in a burner that is located in the door, which has an opening to accommodate the burner. Around the burner there is also refractory. Gases, products of combustion, leave the boiler after giving up heat to boiler internal walls, from where the heat is transferred to the water. The furnace is filled with flame and gases, and tubes are filled with gases, giving the boiler the name - fire-tube.

Economy of boiler operation

How much energy released from fuel is taken up by the boiler water is expressed as an efficiency, which is calculated by several methods. Most simple and widely used, although inadequate for evaluation of seasonal economy of boiler, is "combustion efficiency" (in USA called also fuel-to-water/steam efficiency, which also incorporates jacket losses of a boiler, which are maximum 1%). Combustion efficiency is measured using a stack gas analyzer and by analyzing composition of stack gases (such as O₂, CO₂, CO, soot, excess air or so-called lambda value) and stack temperature, burn efficiency is calculated. To assess total boiler losses over a certain period, "input/output" (I/O) efficiency or "boiler efficiency" is used, since it incorporates all losses of boiler and burner. To accomplish this, the energy available for release from the fuel and energy actually taken up by the water or steam must be known. Not as easy task as measuring combustion efficiency.

Core problem

There has always been a difference between combustion and I/O efficiencies; the difference increases with a reduction in boiler load. The lower the boiler load, the lower the I/O efficiency of the boiler, although at lower loads the combustion efficiency can improve becoming higher than at nominal loads. Boilers have to be designed to cover peak load, and since peak loads seldom appear, boilers generally operate at reduced load, in many cases far below 50%. This generates significant losses, which are attributed as unaccounted loss.

Project goals

Since existing designs of fire-tube boilers provide higher efficiency when the boiler operates at or close to nominal load, there is room for improvement in boiler operation economy. Boiler manufacturers have neglected this as a fact that cannot be avoided. Another improvement is fire-tube boiler design itself, which is more than 150 years old, and which has remained mainly unchanged since it was first used in ships. Because of the perpetuation of the design there are too many tubes, too much refractory and in many cases too small furnace. All of this as a direct consequence of poor knowledge of heat transfer inside a boiler, which is imperative for successful optimization of boiler design. Hence, the project goals follow:

- to improve boiler efficiency at reduced load to increase seasonal boiler efficiency
- to reduce number of boiler tubes
- to eliminate refractory
- to make entire boiler internal area participate in heat transfer.

Project achievements

The above goals, set at project outset in 1987, have been completely met and results proven:

- reduction in boiler efficiency at reduced boiler load is eliminated
- up to 70% fewer tubes (4MW / 400HP boiler of new design comes with just 75 2.5" tubes while conventional design can have up to 237 of them)
- no refractory
- cooled door design that can be applied on fire tube steam boilers including double furnace designs of up to 25MW / 2500HP power
- common platform boiler eliminating various boiler families and enabling sizable cost savings in manufacturing process.

Demo installation

Demo installation was constructed beginning in early 1999 at Tucson Medical Center in Tucson, Arizona, USA (www.tmcaz.com) with three steam boilers of 4MW / 400HP 10bar / 150psi pressure and, or 6-ton steam per hour capacity, respectively. All three boilers are equipped with state of art computer monitoring

equipment, which has been monitoring and logging boiler performance data round the clock since installation. Data indicates a consistent proven up to 15% increase in seasonal I/O boiler efficiency, translating to 5-year installation pay back, instead of 8 as originally planned with new boilers of conventional design. Previous boilers at demo site were of same basic design (2 - pass reverse flue, a product of Swiss boiler company Ygnis, made by its US licensee) installed in 1978, and were operated and maintained well.

PROJECT DESCRIPTION

Introduction

Fire-tube boilers up to 25MW / 2500HP power and 25bar / 360psi pressure for hot water and steam applications represent the most commonly used type of boiler today. There are several designs, which are pretty much the same. The primary difference is how many times the flue-gases change direction inside the boiler and how many tubes there are. Boilers of the most common three-pass design (see **Figure 1**) feature two assemblies of tubes. There is no turn at the rear of the furnace back to the door since the flue-gases pass into first tube assembly then turn 180° and enter the second tube assembly before exiting through stack. The four-pass design is the same as the three-pass with one more tube assembly resulting in more tubes and one more direction change. The two-pass design (see **Figure 2**) has a single tube assembly. The flue-gases make a 180° turn at the rear of furnace back towards the door before entering the tubes and exhausting to the rear.

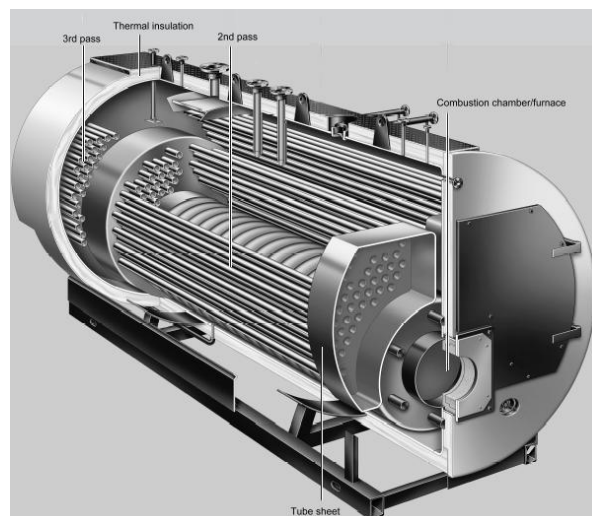


Figure 1: Three-pass fire-tube steam boiler

The number of passes does not affect the extraction of heat from the flue-gases on their way through the interior of the boiler. The amount of extracted heat depends on how much heat transfer surface area there is, how it is distributed (area located in furnace versus in tubes) and the velocity of flue-gases. More passes does not mean more efficiency, it only results in more reversals of the flue-gases flow. Thus, from the heat transfer point of view, there is no advantage of the three- and four-pass designs over the two-pass. Further, more passes means higher cost and weight of the boilers because of the introduction of more tube assemblies, which are more expensive than boiler steel plates.

The one advantage of three- and four-pass fire-tube boiler designs over a two-pass is the elimination of the need for a 180° flue-gas reversal at the rear of the furnace. The result is shorter dwell-time for the combustion products and the reactants involved in NO_x formation, resulting in lower NO_x emissions compared to the two-pass reversing design. As some reductions in NO_x emission can be achieved by relatively simple and inexpensive means, along with the new generation of burners, lower NO_x - emissions can be achieved regardless the type of boiler. Hence, there is nothing advantageous in the three- and four-pass boiler designs over a two-pass design. Thus, a two-pass boiler design with reversing furnace was chosen for the basic design to be extensively upgraded and optimized to achieve the project goals.



Figure 2: Two-pass reverse flue fire-tube hot water boiler

Disadvantages of existing fire-tube boiler design

All fire-tube boilers today share common disadvantages, which are:

- efficiency decrease at reduced load due to significantly weakened heat transfer in part of tubes at reduced load (appearance of dead zone, see **Figure 3**);
- excessive number of tubes;
- presence of refractory, which is heat sink and needs replacement over time;
- some welds are difficult to access making the maintenance work more difficult and costly;
- tubesheet cracking as a result of high gas temperature leaving the boiler furnace.

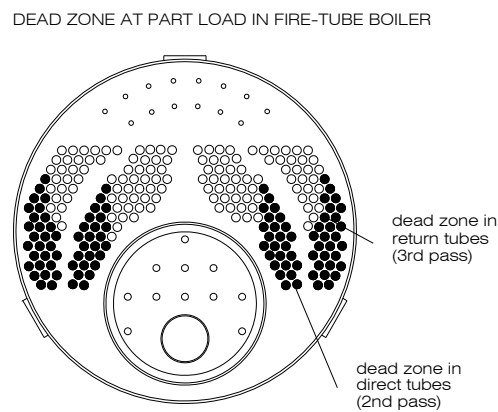


Figure 3: Dead zone in three-pass boiler

The biggest problem is boiler efficiency degradation at reduced boiler load (see **Figure 4**) that can exceed 15%, so the main attention was devoted to this issue. Prepurge usually accounts for 2-3% of these losses, poor thermal insulation of boiler jacket for maximum 1-1.5% and excess air increase at partial load for 2-3%. Thus more than 50% of annual boiler losses are attributed as unaccountable, which origin has been found to be following: Boilers operate below optimal load most of the time although, they are designed to cover peak load. At these lower loads, heat generated by combustion is reduced. This reduced amount of heat, carried by flue gases, flows across a heating surface designed for full load operation. Since there is less heat available to give off, the flue gases can cool down to a level near the surrounding heating surface long before reaching the exit of the boiler. This can take place already in the second pass depending on the number of tubes in the boiler. Thereafter, heat transfer becomes stagnant.

When this condition occurs the temperature of the flue gases, the heating surface wall and the surrounding water/steam tend to be congruent. Since a key factor of heat transfer is temperature difference, it follows that there is very little heat being transferred from combustion product to water when the boiler is at low load. From a thermodynamic point of view this is a loss. Hence, boiler efficiency, tested by flue gas analysis, based on flue gas temperature, can be misleading for actual I/O efficiency can be much lower. The difference in these two efficiencies is commonly attributed to unaccountable loss. 3- and 4-pass boilers are the most affected because their tube/furnace area ratio can reach 30:1 or greater, which means there is 30 or more times area in tubes versus the furnace. The higher the number of tubes in a boiler, the higher the tubes/furnace area ratio the worse the situation.

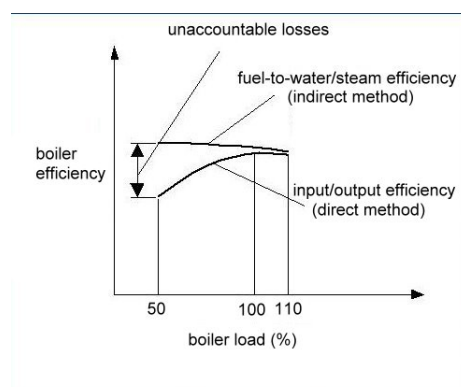


Figure 4: Boiler efficiency curves

Since boiler door is situated in the high temperature zone, the refractory lining is required. This refractory material contributes no benefit to the boiler efficiency. It must be thick enough to minimize heat loss through the door and protect the bare steel, which is unable to withstand that high temperature. Since refractory is a heat sink associated losses cannot be avoided. The solution is a cooled door. This must be done in a user-friendly way. The door becomes another pressure vessel that connects to the boiler shell and becomes useful heat transfer surface. The cumbersome refractory is eliminated along with the consequential maintenance. The cooled door reduces flue gas temperature on tubesheet from up to 1200°C / 2190°F, as found in other boilers, to less than 800°C / 1470°F at nominal load, eliminating tube cracking.

Project unfolding

The following areas were addressed:

- degradation of boiler efficiency at reduced load;
- excessive number of boiler tubes;
- use of refractory;
- amount of boiler internal surface area participating in heat transfer;
- tubesheet cracking;
- elimination of various boiler families and manufacturing cost reduction by developing a boiler on a common platform principle.

Step 1: Fundamental research on heat transfer in boilers

In order to accurately analyze heat transfer in boiler and impact of design changes on boiler performance, the fundamental research on heat transfer in boiler had to be conducted. It has resulted in new theoretical findings that were used in writing dedicated Boiler Design Software. Using it the need to make and test the boilers in laboratory has been reduced to an absolute minimum. The software enables a very accurate prediction and analysis of the heat transfer in fire-tube boilers of arbitrary geometry fired with fossil fuels of arbitrary chemical composition under different operating conditions. The accuracy for heat transfer calculations lie within +/-1.5 % and +5-10% calculating internal gas side pressure drop (a margin of safety is incorporated into the pressure drop calculation to avoid overloading the burner fan by installing too few tubes). The following problem had to be addressed, in order to perform the more accurate computation of heat transfer in fire-tube boilers:

Heat transfer by thermal radiation in boilers

To determine the radiant and convective portion of heat transfer in a fire-tube boiler the effective temperature in each boiler section must be known. Radiation, from the hot flame and flue-gases to a cooled enclosure of a simple geometrical shape, as in the cylindrical furnace in a fire-tube boiler, is described in literature using an approximation. This approach tends to be less accurate since it cannot accurately describe the results of a combination of flame and gas radiation. A new algorithm incorporating a more accurate equation for mean radiant temperature was developed to address this inaccuracy.

Turbulators in boiler tubes

Turbulence promoters (turbulators) are inserts, which increase the rate of convection in the tubes compared to those, which are empty. These devices appear in different shapes. An inappropriate assessment of a turbulators' impact on pressure drop can cause the choking of the burner because its fan would be unable to overcome the increased pressure drop in the boiler due to an inaccurate assessment of the turbulators' combined effect on heat exchange and pressure drop. Today, coiled-wire turbulators are the most widely used. Literature dealing with the analytical assessment of the impact on heat exchange and pressure drop in tubes with coiled-wire turbulators is very scarce. The new algorithm incorporates a more accurate yet simple procedure for analytical assessment of the impact of coiled-wire turbulators on heat transfer and pressure drop in boiler tubes.

Heat transfer by convection in boilers

Convection in boilers takes place simultaneously with radiation. In tubes of a fire-tube boiler up to 95% of heat exchange takes place by the convection. In the furnace heat exchange by radiation is far greater than in the tubes. Calculation of convection is conducted by standard equations for flow in straight tubes and channels. This picture totally changes when gas flow directly hits the surface involved in convection, such as in the case of the cooled rear of the furnace. The rate of convection is much higher in these cases and cannot be assessed by classical equations for straight flow in tubes and channels. Tests showed much lower gas exit temperatures from the furnace than calculated by conventional methods. The new algorithm addresses this special case and provides a solution.

Step 2: Building of prototypes, conducting of tests and evaluation of applied design changes.

During the research and development procedure several boiler prototypes were built and put to extensive tests in laboratory. The test boilers were progressively upgraded, incorporating new to-be-tested technical solutions. At the end of testing five of them had been built with power ranges from 500kW / 50HP in a hot water version to 4MW / 400HP /10 bar / 150psi in a steam one.

Step 3: Implementation and practical verification on actual installation.

In early 1999 three 4MW / 400HP steam boilers (6 ton steam per hour), 10 bar / 150 psi pressure of new design were installed at Tucson Medical Center in Tucson, Arizona in United States of America. There boilers replaced customer's old installation consisting of two 1978, 6MW / 600HP, 10 bar / 150psi pressure, Ygnis type fire-tube boilers made in USA, which were very well maintained. Boilers were operated at less than 50% load on average and had been running mostly on natural gas, and approximately 20% of time on light oil. Modern computerized monitoring equipment has been installed to monitor and log each new boiler's performance round the clock. Seasonal I/O efficiency of replaced boilers was 61.7+/-2% (calculated using fuel higher heating value as common in USA, value (add 8.6% for lower fuel heating value, natural gas)). A seasonal efficiency increase of up to 15% has been observed with new

boilers. Operational and fuel cost factors have translated to savings that reduced the expectations of estimated pay back. The installation, including demolition of old boilers, installation of new ones and commissioning costs, will pay for itself on fuel savings in less than five years, down from 8 as originally expected if conventional new boilers were installed. All technical and performance claims have been proven and properly corroborated beyond any doubt making the new boilers most advanced today.

Summary of project results

The goals set in the beginning of project in 1987 have been met completely, and despite the new technical solutions and numerous advantages no downsides and any negative side effects have been observed. Advanced fire-tube boiler features following advantages over conventional design as found on markets today:

1. Significantly improved efficiency at reduced boiler load and herewith improved boiler seasonal efficiency.
2. No refractory (all surfaces water backed).
3. Up to 70% fewer tubes (4MW / 400HP boiler comes with as low as 75 tubes while conventional same sized boilers have up to 237 of them).
4. Up to 100% intensified heat transfer (up to 50 kW/m² / 2.3 sq.ft./HP in average).
5. Minimized jacket losses.
6. Suitability for all burners (design program can incorporate any design).
7. Increased heat transfer in furnace (up to 80% of released heat can be taken up in furnace alone, 50% less in conventional 3-, and 4-pass design).
8. All welds easily accessible from all sides.
9. Significantly reduced occurrence of tubesheet cracking due to significantly reduced temperature on tubesheet due to cooled door.
10. Cooled door design that meets all criteria, works on steam boilers and can be applied also on double furnace boilers.
11. Improved tubes/furnace area ratio to 3 to 1 (less than 3 times more area in tubes than in furnace, in conventional boiler design it is up to 26 to 1, and even more).
12. Improved furnace/tube heat transfer ratio to 4 to 1 (furnace takes up as much as 4 times more energy than tubes, much more than in conventional design).
13. No change in production technique, no additional requirements for burner, operation or maintenance.
14. Reduced maintenance cost.
15. Common platform principle successfully implemented eliminating the need for various boiler families (2-,3-, and 4-pass, fire-box, dryback, wetback etc.).
16. Retrofit of installed boilers possible enabling upgrading to Warga design with all its advantages while boiler stays in place.

Performance data

Old installation

- two fire-tube steam boilers
- type: Ygnis reverse flue
- make: Sellers Engineering, USA
- nominal power: 6MW / 600HP
- pressure: 10 bar / 150 psi
- burner: dual fuel forced draft (no dedicated combustion controls)
- year of installation: 1978

New installation

- three advanced fire-tube steam boilers
- make: mioMETAL, Slovenia
- nominal power: 4MW / 400HP
- pressure: 10 bar / 150 psi
- burner: dual fuel forced draft Weishaupt with Autoflame combustion controls
- year of installation: 1999

Operating conditions

- lead & lag positions are changed monthly to maintain relatively equal time run of about 4500 hours annually
- one boiler is kept as reserve or down for maintenance
- peak boiler load occurs in the Spring and Summer when operating absorption chiller (adjusted for operational issues)
- peak heating load is Fall and Winter
- Spring/Summer peak load is estimated at 7.25 tons of steam per hour at 8.3 bar / 120 psi pressure
- winter peak is estimated at 6.35 tons of steam per hour
- fuels: natural gas (app. 80% of time), light fuel oil (app. 20% of time)
- natural gas consists of 97% methane CH₄ and it is delivered at 0.48 bar / 7 psi and regulated down to 50 mbar / 0.72 psi.

Monitoring equipment

State of the art boiler performance monitoring equipment has been used to calculate instant and seasonal boiler efficiency on direct method, being most relevant one:

- make: Rosemount Inc.
- model: 3095 M (with all necessary elements and software)
- declared measurement uncertainty: +/- 1%
- overall measurement uncertainty: less than +/- 2%.

Comparison of seasonal efficiencies

In tables to follow the efficiency of old and new boiler installations at demo site is expressed as energy-in / energy-out ratio. Former stands for heat delivered from combustion and the latter for heat delivered to steam. This so called direct method has been chosen for it contains all the losses, while the combustion efficiency serves only as instant indicator of boiler performance. Efficiency numbers below are calculated with fuel (natural gas) higher heating value (8.6 to be added for fuel lower heating value).

a) old installation

- efficiency displayed by flue gas analyzer: 78 - 80%
- jacket (stand by) losses at nominal load: 1.5 %

Table 1: Seasonal Input/Output efficiency¹ of old installation at demo site

year: 1997	energy to steam BTU	energy from fuel BTU	I/O efficiency (%)
January	10,509,440,000.00	17,323,579,200.00	60.67
February	9,764,328,000.00	15,912,000,000.00	61.36
March	10,712,112,000.00	17,136,000,000.00	62.51
April	9,588,240,000.00	15,912,000,000.00	60.26
May	13,142,016,000.00	20,808,000,000.00	63.16
June	12,854,700,000.00	20,440,800,000.00	62.89
July	13,445,319,200.00	21,520,000,000.00	62.48
August	13,216,966,500.00	21,297,600,000.00	62.06
September	12,516,379,200.00	20,196,000,000.00	61.97
October	10,609,440,000.00	17,136,000,000.00	61.91
November	8,644,320,000.00	14,076,000,000.00	61.41
December	11,379,480,000.00	18,960,576,000.00	60.02
Total	136,382,740,900.00	220,718,555,200.00	
Average	11,365,228,408.33	18,393,212,933.33	61.72

year: 1997	energy to steam kJ	energy from fuel kJ	I/O efficiency (%)
January	11,087,459,200.00	18,276,376,056.00	60.67
February	10,301,366,040.00	16,787,160,000.00	61.36
March	11,301,278,160.00	18,078,480,000.00	62.51
April	10,115,593,200.00	16,787,160,000.00	60.26
May	13,864,826,880.00	21,952,440,000.00	63.16
June	13,561,708,500.00	21,565,044,000.00	62.89
July	14,184,811,756.00	22,703,600,000.00	62.48
August	13,943,899,657.50	22,468,968,000.00	62.06
September	13,204,780,056.00	21,306,780,000.00	61.97
October	11,192,959,200.00	18,078,480,000.00	61.91
November	9,119,757,600.00	14,850,180,000.00	61.41
December	12,005,351,400.00	20,003,407,680.00	60.02
Total	143,883,791,649.50	232,858,075,736.00	
Average	11,990,315,970.79	19,404,839,644.67	61.72

¹ Calculated with fuel higher heating value (8.6 percentage points to be added for lower fuel heating value, natural gas).

b) new installation

- efficiency displayed by flue gas analyzer: 79.5 - 81.2%
- jacket (stand by) losses at nominal load: 0.3 %

Table 2: Seasonal Input/Output efficiency² of new installation³ at demo site

year: 2000	energy to steam BTU	energy from fuel BTU	I/O efficiency (%)
January	8,805,465,545.28	11,788,055,976.94	74.70
February	7,993,123,247.71	10,759,019,483.45	74.29
March	8,643,870,333.64	11,681,110,843.82	74.00
April	8,083,167,295.49	10,861,851,988.49	74.42
May	8,431,521,056.42	11,318,680,401.88	74.49
June	8,522,852,524.49	11,476,581,365.42	74.26
July	8,652,185,628.79	11,677,000,824.71	74.10
August	8,880,909,367.80	11,903,666,302.90	74.61
September	8,183,026,845.56	11,006,827,001.68	74.35
October	8,007,401,281.79	10,734,221,018.04	74.60
November	6,991,533,563.88	9,390,181,527.45	74.46
December	7,725,351,288.23	10,385,132,554.71	74.39
Total	98,920,407,979.05	132,982,329,289.51	
Average	8,243,367,331.59	11,081,860,774.13	74.38

year: 2000	energy to steam kJ	energy from fuel kJ	I/O efficiency (%)
January	9,289,766,150.27	12,436,399,055.68	74.70
February	8,432,745,026.33	11,350,765,555.04	74.29
March	9,119,283,201.99	12,323,571,940.23	74.00
April	8,527,741,496.74	11,459,253,847.86	74.42
May	8,895,254,714.52	11,941,207,823.99	74.49
June	8,991,609,413.33	12,107,793,340.52	74.26
July	9,128,055,838.37	12,319,235,870.07	74.10
August	9,369,359,383.02	12,558,367,949.56	74.61
September	8,633,093,322.06	11,612,202,486.77	74.35
October	8,447,808,352.29	11,324,603,174.03	74.60
November	7,376,067,909.89	9,906,641,511.46	74.46
December	8,150,245,609.09	10,956,314,845.22	74.39
Total	104,361,030,417.90	140,296,357,400.43	
Average	8,696,752,534.82	11,691,363,116.70	74.38

² Calculated with fuel higher heating value (8.6 percentage points to be added for lower fuel heating value, natural gas).

³ Minimum observed values