MODEL PREDICTIVE PLANT-WIDE ENERGY AND PROCESS PERFORMANCE ANALYSES FOR A LARGE-SCALE MUNICIPAL WASTEWATER TREATMENT PLANT

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Abstract

In this study, the process performance in terms of effluent quality, the sludge production and the biogas potential was simulated and compared with the data of real wastewater treatment plant with the capacity of 1,400,000 PE in Antalya, Turkey. The energy content of undigested primary and biological sludge were measured to be 16.33 MJ/kg (3,900 kcal/kg) and 13.21 MJ/kg (3,155 kcal/kg) of sludge on dry basis. The thermal and electrical energy production generated form sludge was examined by using annual data. In addition, the energy balance in the system was evaluated by incorporation of additional sludge disintegration, anaerobic digestion and sludge incineration processes. The energy generation through biogas production and heat recovery from incineration was thoroughly evaluated in combination with simulation based on process analysis.

Keywords

Sludge energy, modeling, calorific value, advanced digestion, incineration

Introduction

Sludge management is known as a bottleneck in wastewater treatment plant operation as the selection of treatment and disposal alternatives require an elaborative evaluation to maintain an economic and sustainable solution. The quantity and quality of sludge exhibit great variations depending upon the influent wastewater characterization and local environmental conditions and wastewater treatment process. On the other hand, the excess sludge (primary and biological) contains high amounts of organic matter that have high energy contents. In addition, the state of the art sludge treatment technologies focus on energy generation options such as anaerobic digestion, advanced digestion (digestion with disintegration) and sludge incineration. The selection of a sludge treatment scheme should be compatible with the wastewater stream to secure optimal process performance. Recent developments in process modeling enable evaluation of the real-time process performance considering wastewater and sludge treatment streams together with energy consumption and generation.

After preliminary treatment, biological wastewater treatment has been played important role in water environment and ecological protection to remove organic matter together with nutrients. While during the wastewater treatment, a large amount of excess sludge can be formed due to the biomass growth. However, treatment and disposal of the excess sludge has become even more complex and costly than the wastewater because of the relevant strict legislations with respect to sludge disposal and the land limitation for landfill application.

In the last decade, there is an increasing trend in implementing measures that consumes less energy for sustainable operation. Implementing energy conservation measures, using less expensive alternative energy sources or generating energy on-site are just a few examples of the ways that facilities are saving on their energy bills.

The main objectives of the sludge treatment technologies are the reduction of the volume and mass of the sludge, elimination of the microbial activity and pathogens, prevention of odor release, and recovery of nutrients and/or energy of the material. Biological treatment technologies, like composting and anaerobic digestion, are able to reduce the volume of the sludge by 5–50%. The advantage of biological treatment is the possibility to recover the nutrients and humus to the ecosystem. Excess sludge produced from the wastewater treatment is very valuable energy resource because of its considerable calorific content. The calorific value of sewage sludge depends exclusively on the amount of organic matter in the dry solids (DS). An average calorific value of 23 MJ/kg can be assumed for 10% organic matter (Reimann et al.,1990)

Incineration, which can treat large varieties of heterogeneous wastes, is one of the available treatment tools that can be used within integrated waste management systems. During incineration, the flue gases created contain the majority of the available fuel energy as heat. The organics in the waste is burn in gas phases when they have reached their necessary ignition temperatures and come into contact with oxygen. The actual combustion process takes place in gas phase in fractions of seconds and simultaneously releases energy. This leads to a thermal chain reaction and self-supporting combustion, i.e. there is no need for the addition of other fuels. (Autret et al. 1996)

In the last 15 years, advanced sludge treatment processes of thermal hydrolysis (THP) and incineration, etc. generate energy thqt is used for sludge removal process. Advance digestion processes all aim to improve the digestibility of sewage sludge, increasing the yield of gas. Therefore, to increase the disintegration of sludge; ultrasound, microwaves, enzyme addition etc. are used. For example, the extraction of enzymes is significant mainly because of: recovery of valuable product from the activated sludge and second that these enzymes could be used to advance biodigestibility of sludge and subsequent biogas generation during the anaerobic digestion. (Shang et al. 2013) THP involves using a high temperature (165°C) and pressure (7 barg) for 30 min to disrupt and solubilize sludge before feeding it to a conventional digester. The process also homogenizes the sludge so that it is more digestible resulting in increased methane production and a smaller volume of digester (Kepp 2000). Across the world there are 23 full scale THP sites either in operation or construction that will process 445,000 Tonnes of Dry Solids (TDS) p.a. (Cambi 2010). Incineration is the chemical reaction of oxygen with combustible material. Waste is generally heteregenous material, consisting essentially of organics, minerals, metals and water. During the incineration, the flue gases created contained the majority of the available fuel energy as heat.(Autret et al.2006)

In this study, our aim is to examine the operation scenarios which is constitute of different mass flow of primer and seconder sludge and to determined energy requirements under optimal process operation by securing the discharge limits provided for organic carbon and nutrients (N,P). In this regard, current operation of the WWTP was evaluated with the combinations of drying, incineration and THP processes.

Materials and Methods

Process Description of Wastewater Treatment Plant

Hurma municipal WWTP is located in the western part of Antalya, Turkey. The final design for the treatment plant is 1,400,000 PE with the hydraulic capacity of 210,000 m^3/day. Under current operation the plant receives 135,000 m^3/day wastewater. Under peak weather conditions, the flow rate increases by the factor of 1.8.

The process was selected for organic carbon and nutrient removal. The layout of WWTP is shown in Figure 1. The pretreatment system contains coarse and fine screens together with grit/grease removal. After pre-treatment, the wastewater is subjected to primary sedimentation, where the settlable solids are removed. The retention time of primary sedimentation was adjusted to nearly 1 hour. Pre-settled wastewater is transferred to anaerobic selector and 2 of carousel type activated sludge reactors. The sludge age of the carousel is adjusted to 8 days. Each of carousels is equipped with diffusers and slow speed mixers for generating aerobic and anoxic regions within the reactor.

The characteristics of influent wastewater were summarized in Table 1. After the Bio-P reactor, the mixed liquor is introduced to anoxic reactor with the anoxic fraction (V_D/V) of 30-40%. The remaining aerobic section was aerated to provide nitrification. The dissolved oxygen concentration was adjusted to 1-2 ppm. In carousel reactor the anoxic mass fraction is adjusted via adjusting air flows in the diffuser grids. The RAS rate was set to 100% on the basis of dry weather flow.

Figure 1: General Layout of West Antalya (Hurma) WWTP, Turkey

Currently, one line of the carousel system is in operation. Activated sludge is then diverted to 8 secondary clarifiers. However, 4 of the clarifiers were in operation. The settled activated sludge is recycled back to the anaerobic selectors. The excess biological sludge is thickened by table thickeners and mixed with primary sludge for further mesophilic anaerobic digestion

(AD) process. The retention time of AD is adjusted to 23 days. Treatment plant has 4 digesters and only one tank is under operation. The actual capacity of each digester is 9,000 m^3.The average VSS reduction rate of approximately 30% was recorded. Generated biogas was desulfurized and burned in gas engine for the electricity and heat production. After the anaerobic digestion, the sludge is dewatered by decanter centrifuges and dried thermally. The dewatered and dried sludge have the DS contents of 24% and 95%, respectively. The dried sludge is sent to the cement factory for energy production. There is a diesel generator with the capacity of 7,020 MJ/h (1,950 kW) in existing WWTP. The generator is operated by using of biogas for electricity and heat energy production. Produced electricity is used in energy requirement of WWTP. The total power capacity of WWTP for existing situation is 10,800 MJ/h (3,000 kWh.). The biogas burning capacity of Gas Engine is approximately 850 m^3/h biogas is used under full capacity.

Table 1: Average Influent Wastewater Characterization (Year 2012)

Parameter	Unit	Value
Total COD, C_T	mgO_2/L	605
Influent BOD_5	mgO_2/L	290
Soluble COD, S_T	mgO_2/L	206
Volatile Fatty Acids, VFA	mgO_2/L	20
Total Suspended Solids, TSS	mg/L	313
Volatile Suspended Solids, VSS	mg/L	250
Settled COD	mg/L	465
Total Nitrogen, TKN	mgN/L	48
Ammonia Nitrogen, NH_4-N	mgN/L	26
Total Phosphate, TP	mgP/L	5.2
Ortho Phosphate, PO_4-P	mgP/L	3.4
Total Alkalinity, S_{ALK}	mmol/L	10
Temperature Range , T	°C	12-28

Performance and Mass Balance Analyses with Simulation

In order to simulate the BNR and Anaerobic Digestion processes Activated Sludge General Model used. Plant layout including two bio-phosphorous tanks, one aeration tank and 5 final clarifiers were introduced to Biowin as similar to the real plant operation. The carrousel type activated sludge tank was simulated with ten reactor in series (Abusam and Keesman, 1992). Yearly based average influent data was used to evaluate the operation of full scale wastewater treatment. The activated sludge configuration was shown in Biowin 3.1(Figure 2). The model was calibrated using annual data of effluent nitrogen (NH_4, NO_3), phosphorus (TP, PO_4), COD and TSS. The MLSS concentration in AS and RAS; dissolved oxygen concentrations along the carousel channel were also calibrated (data not shown). The calibrated model is then used for simulating yearly average performance of the activated sludge system and also different operation configuration of sludge treatment units. A relation between sludge composition and energy content was driven after process simulation.

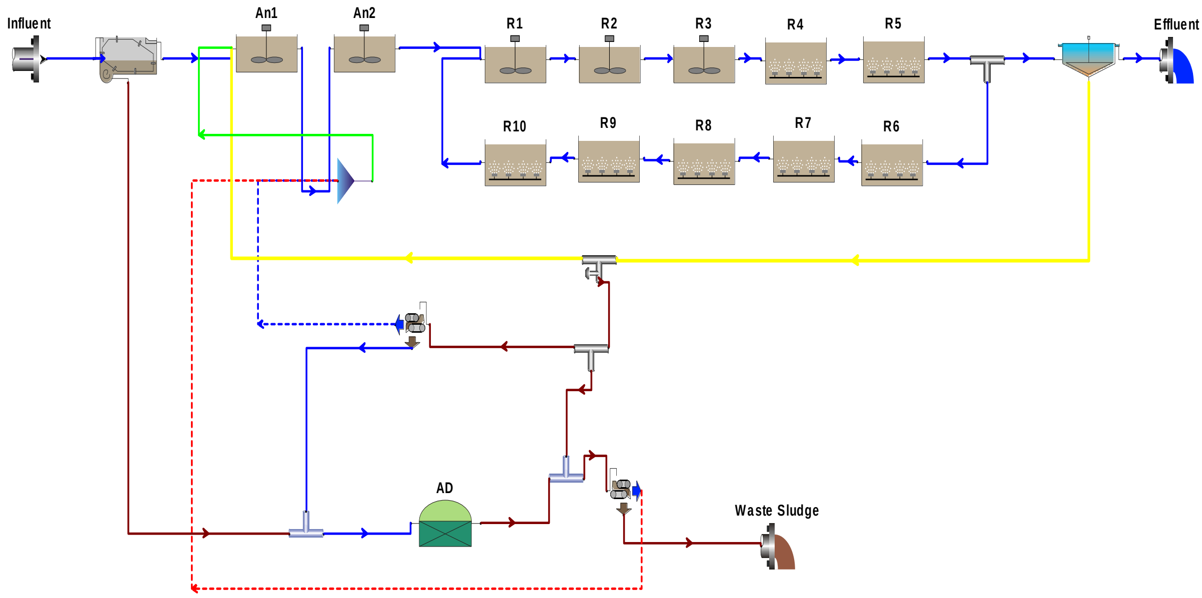

Figure 2: Configuration of Wastewater Treatment Plant used in Biowin 3.1.

Energy Balance of Solids in Wastewater Treatment

The energy balance was established on the basis of mass balance which refers to Figure 2. During establishing of energy balance, energy contents of primary, secondary and digested sludge were measured, independently. According to analyses result of the energy contents, the energy generation capacity of sludge in each unit of treatment plant was determined according to overall solids mass balance of treatment plant. Energy content of final dewatered and dried sludge and biogas production capacity and its energy content were determined. In addition to that the energy generation capacity of planned incineration was included in evaluation together with current drying system. Further analyses deal with the capacity of biogas energy was also calculated. The calculation of electricity and heat energy content of biogas were performed. The CHP system capacity was defined as 7,020 MJ/h(1,950 kWh) in existing WWTP. The conversion factors of biogas into electricity and heat energy is 45% and 45%, respectively. As mentioned in the previous section, in the current situation, 50% of the secondary (biological) sludge mass rate is fed to the anaerobic digester. The remaining mass rate is directly conveyed to the final dewatering unit. Different operation scenarios were configured on the basis of calibrated model and changing of energy balance was analyzed. Furthermore, considering the discharge criteria, operation of primary sedimentation tanks with different efficiencies were emphasized and effect on energy balance and wastewater treatment efficiencies were evaluated.

Results and Discussion

Calculation of Process Performance and Mass Balance

In order to secure the effluent TN concentration, the activated sludge reactor is operated with 30% anoxic mass fraction (V_D/V). During operation, the TSS removal ratio of 40% was recorded in primary sedimentation step (Table 1). In simulations, mass balance over the system was secured by using the same solids retention time (SRT) and MLSS concentrations in aeration basin. The model calibration was performed using the steady state calibration under yearly based influent values corresponding to different process temperatures. The model parameters were manually tuned according to existing annually oxygen requirement and average annually composite TN, TP, COD and TSS effluent concentrations as mentioned above (see Table 2) for year 2012.

The oxygen requirement was simulated as 1,716 kgO_2/hour that corresponds to an airflow rate of 32,000 Nm^3/hour which was in concert with real system. The overall sludge production was simulated to be 28,901 kg DS/day including primary sludge and biological (secondary) excess sludge. The fractions of primary and biological excess sludge were determined to be %42 and %58, respectively. The effluent total nitrogen (TN) concentration was 8.1 mg N/L together with the Total Phosphate (TP) level of 0.95 mg P/L. On the other hand, the effluent TSS and COD concentrations were calculated to be 7 and 37 mg/L, respectively which are also fits well in real conditions. It is important to note that, in existing situation, only 50% fraction of biological (secondary) sludge is being fed to the anaerobic digester, other half of secondary sludge is directly transferred to the dewatering unit. For this reason, the model calibration was performed according to the existing WWTP operation mode. The ratio of VSS/SS for the primary, secondary and digested sludge was measured and calculated as 75%, 66% and 64%, respectively.

Analyses of Process Performance and Energy Content

First, the process performance simulations were conducted to envisage the effects of TSS removal efficiency of primary sedimentation. The comparison was made for the TSS removal ratio of 40% and 50% which could be applied in the operation. The effluent of TN and TP values increased by the factor of %30 and %40, respectively. As a result the effluent nutrient concentrations were increased since the organic carbon is utilized for the energy production rather than using for nutrient removal. The acronym of "S" in Table 2 illustrates the scenarios, and "current" governs the current operational condition.

In current operation (see Table 2), the effluent quality can meet the discharge limits of 91, 271 EEC Urban Wastewater Treatment Directive. This condition could be secured by diversion of the 50% flow of thickened biological sludge to anaerobic digester (AD) at 40% of PST efficiency. The remaining part was sent to the dewatering unit. It is important to note that the effluent quality of TP could not be provided due to the fact that the reject stream conveyed nearly 20% additional nutrient load back to the system. This could be remedied by applying N, P recovery in the system.

On the right hand side of the table summarizes the conditions where nutrient recovery is virtually available. In this case, the system could handle TN and TP removal at 50% PST efficiency together with sending 100% flow of biological sludge to AD. Thus, the TP and TN removal ratios were enhanced in the order of approx. 25% and 40%. It is important to note that the recovery effect is more pronounced when more primary sludge is settled prior to the activated sludge reactor. It is noteworthy to mention that the VSS destruction in AD was 30-35% on the basis of long term operation of the system. The biogas production was calibrated using real data with 5,112m^3/day and 5,181 m^3/day corresponding to 2 different PST removal efficiencies of 40% and 50%, respectively.

The calorific values for primary, secondary and digested sludge have been measured as 16.33 MJ/kg (*3,900 kcal/kg*), 13.21 MJ/kg (*3,155 kcal/kg*), 11.50 MJ/kg (*2747 kcal/kg*) respectively of which those values comparable with to the results of Reimann et al. (1990). Table 2 given below summarizes the process performance with respect to COD, TN, TP together with energy content of different sludge types generated from WWTP. The energy contents were calculated on the basis of measured calorific value and VSS contents of the WWTP sludges (results not shown).

Based on the assumptions made, daily biogas energy production could be increased from 121,578 MJ up to 145,793 MJ of energy by yielding 20% difference when TSS removal in PST is increased. Nearly, the same amount of energy could be obtained by sending 100% of biological sludge to the AD. It is clear from Table 2 that, daily energy produced from biogas around 145,793 MJ could be raised to 174,976 MJ with the difference of 20% (without N,P recovery system). Unfortunately, under this condition, the effluent quality fails to meet the discharge standards with respect to TP. However, the effluent quality is able to meet the discharge TP limit by implementing nutrient recovery. On the other hand, additional energy of around 30,000 MJ/day due to biogas becomes available for utilization. Additional energy gain can be guaranteed due to additional nitrification because of increased nitrogen return load. However, this is beyond the scope of this paper.

If one compares the gross incineration energy available in the (dry) sludge, decreased when 100% of secondary sludge is sent to AD together with all primary sludges. In this case, the biogas potential increases, on the other hand the daily energy available for incineration in the digested sludge is decreased. The calculations shown in Table 2 summarizes that increase in biogas energy is higher than that of increase in energy available for incineration for Antalya WWTP when 100% of biological sludge is digested with PS. However, nutrient recovery options should be implemented in order to secure effluent quality and utilize the available energy generated from digestion. Therefore, to increase the biogas production, thermal hydrolysis system was analyzed for its effects on energy balance of existing WWTP.

Table 2: **Comparison for Different Operating Scenarios of WWTP**

PLANT OPERATION	**No recovery from reject streams**				**N,P recovery from reject streams**			
	Current	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
% Removal of TSS at Primary Sedimentation →	40%	50%	40%	50%	40%	50%	40%	50%
% Secondary Sludge to Digester →	50%	50%	100%	100%	50%	50%	100%	100%
Effluent Quality (mg/L)								
Total COD	37	37	38	38	35	35	35	35
Total Phosphorus, TP	0.95	1.00	1.20	1.30	0.78	0.82	0.70	0.80
Total Nitrogen, TN	5.1	7.7	7.5	9.5	3.9	4.9	3.9	4.9
Sludge Production (kgDS/day)								
Primary Sludge	16,271	20,337	16,268	20,338	16,271	20,337	16,268	20,338
Secondary Sludge	21,893	19,553	22,602	20,182	20,897	18,599	20,877	18,744
Digested Sludge	20,863	22,772	29,241	30,589	20,492	22,426	28.466	29,651
Dewatered Sludge	31,208	31,898	28,896	29,977	30,322	31,091	27,866	29,058
VSS/SS Ratio (%)								
Primary Sludge	76	76	76	76	76	76	76	76
Secondary Sludge	66	67	66	67	66	68	67	68
Digested Sludge	65	66	64	65	66	67	65	66
Dewatered Sludge	66	67	64	65	66	67	65	66
Biogas and Incineration Energy (MJ/day)								
Biogas Gross Energy	121,578	145,793	160,030	174,976	119,962	144,415	151,785	170,169
Incineration Gross Energy	298,672	305,272	254,237	263,734	290,188	297,549	245,175	255,063
Energy Content of Sludge (MJ/day)								
Primary Sludge	265,681	332,100	265,632	332,100	265,678	332,100	245.402	332,100
Secondary Sludge	289,200	258,282	298,566	266,602	276,047	245,680	275,771	247,596
Digested Sludge	239,951	261,903	339,073	351,816	235,681	257,924	327,391	341,027

Effects of the State of Art Sludge Technologies on Mass and Energy Balance

This section deals with the analysis of thermal sludge hydrolysis process to be applied to the biological sludge generated from activated sludge unit. In this regard, new energy balance flow diagrams and discharge parameters of the treatment plant were evaluated. The aim is increasing the energy generation also considering the discharge limits. The energy gains and effects of THP on the solids energy balance of existing WWTP. According to results given in Table 2, the %100 capacity of secondary sludge digestion with %50 efficiency of primary sludge removal efficiency was obtained for analysis. The maximum biogas production capacity was obtained. Therefore, this scenario was evaluated to maximize the biogas production by means of implementation of thermal hydrolysis process.

In this respect, the system was added to model configuration and mass and energy balances were determined. According to the process implementation; the primary sludge and secondary sludge are mixed and pre-dewatered to approximately 16.5% DS. Then, the mixed sludge is fed to three parallel THP reactors. The hydrolyzed sludge is diluted to about 11% DS and fed to one digester. Thermal hydrolysis combustion system is required 1,154 kW of thermal energy to generate heat. Decrease in sludge volume by raising the DS level, approximately 7,000 m^3 of digestion volume to get 18 day HRT became adequate, therefore one digester can be perfectly sufficient for digestion. The gas production was estimated to be 15,300 Nm^3/day at a VSS destruction ratio of 57%.

If an incineration system is integrated with thermal hydrolysis system, approximately 209,000 MJ of energy could be generated from the sludge. This generated energy can be used for internal steam production and for sludge drying. The energy requirement of sludge drier plant will be reduced to 172,800 MJ/day because of the increase in DS content of dewatered sludge (32%). Also 15,300 m^3/day biogas production corresponds to 363,593 MJ/day of energy. The energy of 60,570 MJ/day heat from biogas can be used for sludge drying operation. The rest of energy can be used in CHP system by yielding 71,280 MJ/day (198.000 kW) electrical energy. A basic WWTP scheme governing the mass/energy balances of (a) current operation and (b) THP implementation for existing WWTP are shown in Figures 3 and 4, respectively. On the other hand, during the dewatering operations, approximately 530 kg/day nitrogen and 473 kg/day additional phosphate loads will expected to return back to the system. The additional load induced as a side effect of advanced digestion is expected to double the effluent WW characteristics at current operation. The model simulation shows that the anaerobic hydrolysis rate should be increased from 0.22 day to 1.2 day^{-1} to get 57% VSS destruction.

Conclusions

In conventional WWTPs, the organic carbon in wastewater is both utilized for nutrient removal together with energy production. As a result, lowering discharge limits will necessitate more carbon to be diverted to treatment rather than energy production. In this respect, after meeting the effluent limits reasonably, the organic carbon in primary (and also secondary) sludge can be used for energy optimization. However, the wastewater, biomass and process configuration affects the energy contents of biosolids generated during municipal wastewater treatment. The primary sludge digestion is more effective in biogas production due to the organic content of settleable solids.

The advanced digestion process could be implemented to increase the biogas yield considerably. However, the phosphate and nitrogen in reject waters should be taken under control by implementing appropriate recovery technologies. The activated sludge models should also include advanced digestion processes. However, more studies should be conducted to reveal the degradation characteristics of sludge at local conditions.

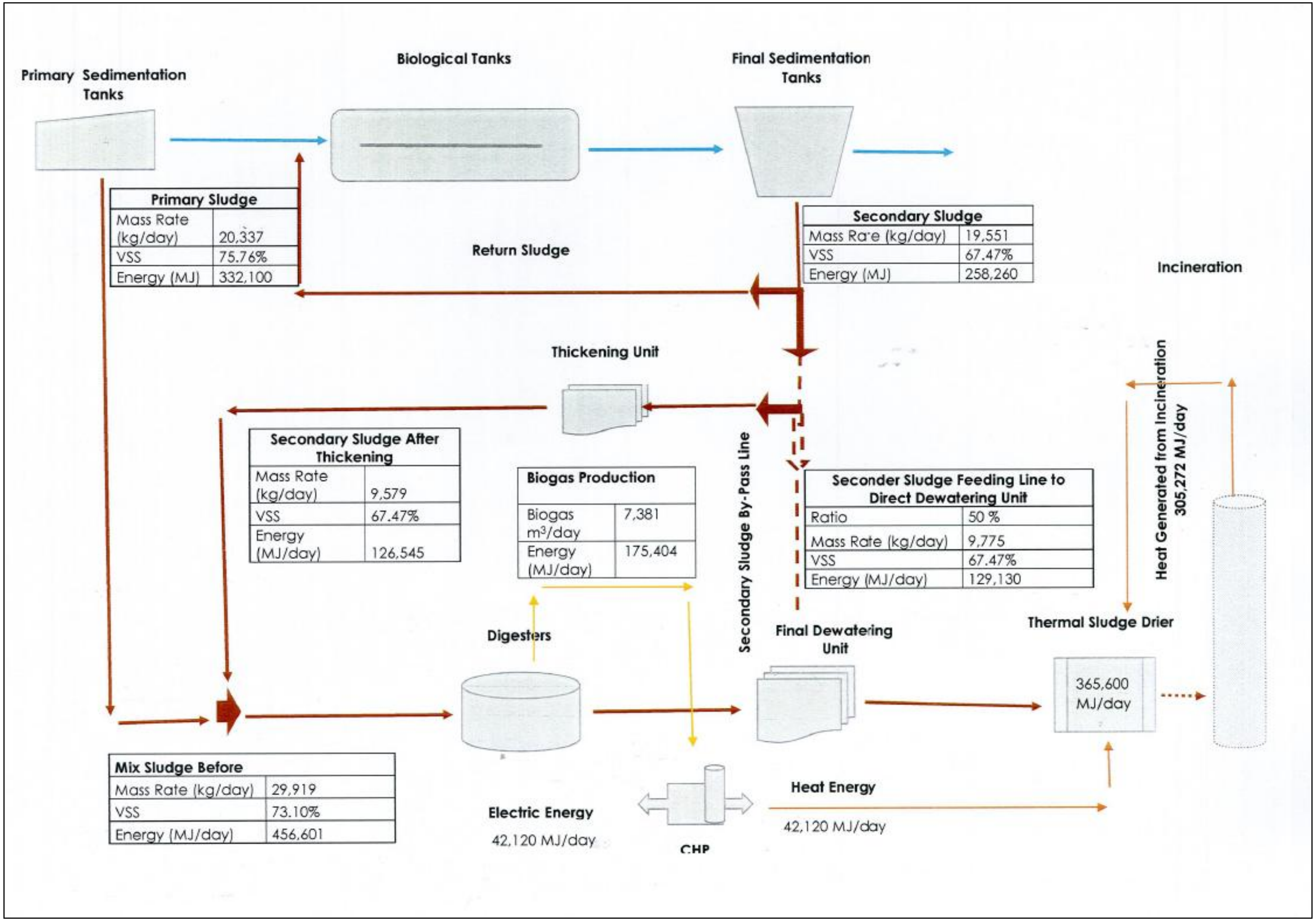

Figure 3: Mass and energy flows in Hurma WWTP for Optimum Efficiency

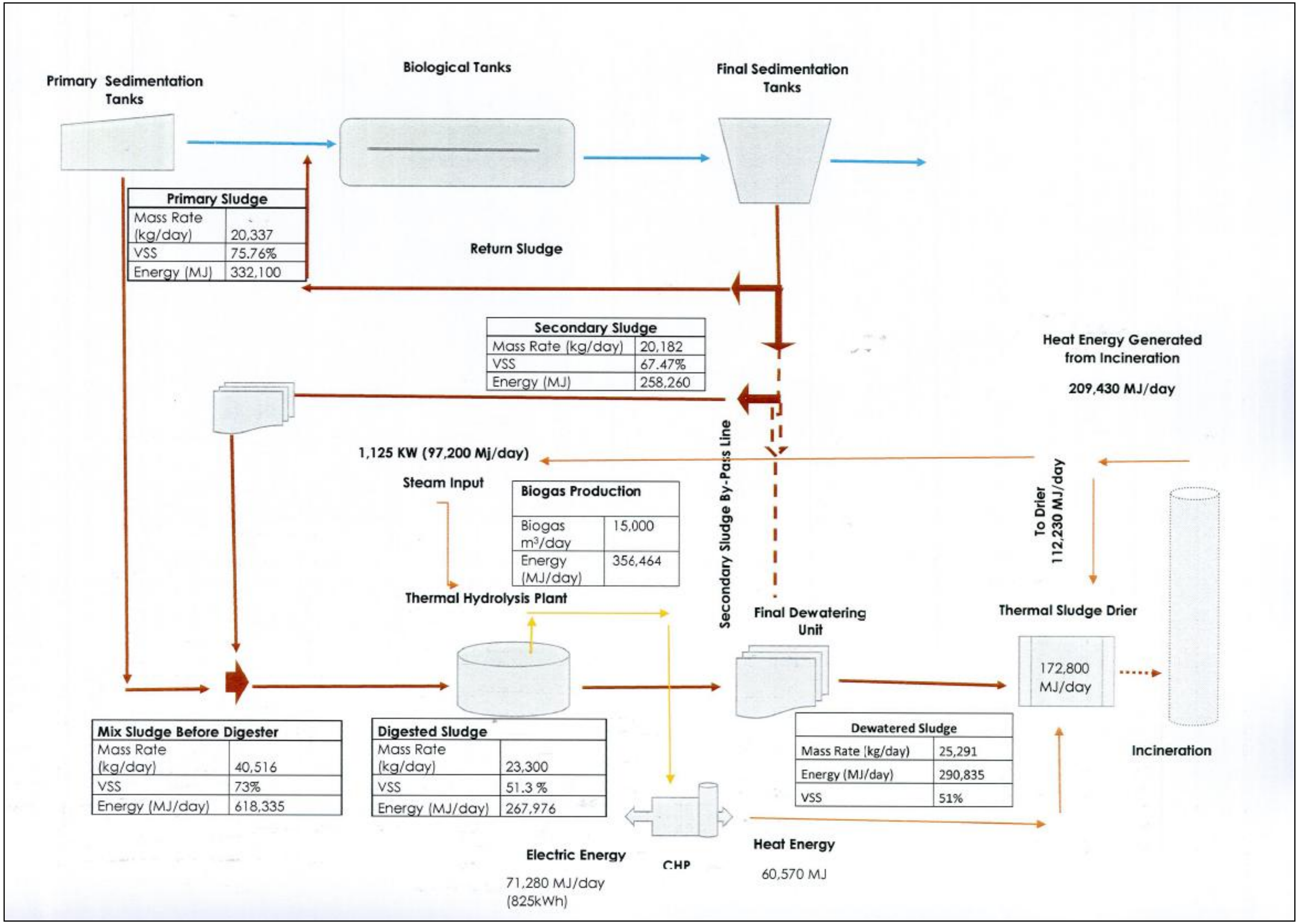
Primary Sedimentation Tanks
Biological Tanks
Final Sedimentation Tanks
Primary Sludge
Mass Rate (kg/day) 20,337
VSS 75.76%
Energy (MJ) 332,100
Return Sludge
Secondary Sludge
Mass Rate (kg/day) 20,182
VSS 67.47%
Energy (MJ) 258,260
Heat Energy Generated from Incineration
209,430 MJ/day
1,125 KW (97,200 Mj/day)
Steam Input
Biogas Production
Biogas m3/day 15,000
Energy (MJ/day) 356,464
Thermal Hydrolysis Plant
Secondary Sludge By-Pass Line
To Drier 112,230 MJ/day
Final Dewatering Unit
Thermal Sludge Drier
172,800 MJ/day
Incineration
Mix Sludge Before Digester
Mass Rate (kg/day) 40,516
VSS 73%
Energy (MJ/day) 618,335
Digested Sludge
Mass Rate (kg/day) 23,300
VSS 51.3 %
Energy (MJ/day) 267,976
Dewatered Sludge
Mass Rate (kg/day) 25,291
Energy (MJ/day) 290,835
VSS 51%
Electric Energy
71,280 MJ/day (825kWh)
CHP
Heat Energy
60,570 MJ

Figure 4: Mass and energy flows in Hurma WWTP with Thermal Hydrolysis for Optimum Efficiency

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References

Abusam A. and Keesman K.J. (1999). Effect of number of CSTRs on the modelling of oxidation ditches: steady state and dynamic analysis, *Med. Fac. Landbouww. Univ. Gent*, 64/5a.
Lien-Lo, S. and Tiyangi, V.K.(2013). Sludge: A waste or renewable source for energy and resources recovery; Renewable and Sustainable Energy Reviews;25/708-728

Barber WP. (2005). The effects of ultrasound on sludge digestion, The Charted Institution of Water and Environmental Management;19/2-7.

Autret, E, Berthier F., Luszezanec A., Nicolas F. (2007). Incineration of Municipal and Assimilated Wastes in France: Assesment of latest energy and material recovery performances; Journal of hazardous Materials B139/569-574

Wentzel M.C., Ekama G.A.,Marais G.v.R. (1992). Processes and modeling of nitrification denitrification biological excess phosphorus removal systems-a review, *Wat.Sci.Tech.*,25(6),59-82

Reimann D.O. (1990). Problems about sewage sludge incineration" Müllheizkraftwerk Stadt und Landkreis BambergRheinstr. 6, D-96052 Bamberg, F.R.G.

Horttanainen M., Kaikko J., Bergman J., Pasila-Lehtinen M., Nerg J. (2010). Performance analysis of power generating sludge combustion plant and comparison against other sludge treatment Technologies, Applied Thermal Engineering, 30, 110–118.