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Regional Supply of Energy from Small Scale Biogas Plants - Discovering Alternative Heat Markets in Denmark

Rikke Lybæk* and Tyge Kjær

Abstract— *This paper argues, among other things, that local biogas Combined Heat and Power plants (CHP) that distributes district heating should have first priority when selecting a distribution option, if a sufficient winter and summer heat market can be identified. In this way the energy will be produced and consumed locally with high energy efficiency and environmental benefits as a consequence. Due to long heat market distances, or due to an already saturated local heat market, this might not always be an opportunity. In such situations it is beneficial to look at other distribution options. The supply of e.g. non-upgraded city gas to households, and upgraded biogas to the natural gas (Ngas) network, were found to be feasible in such situations. It is further concluded that non-upgraded biogas distributed in separate gas networks is an option, primarily for industry, to cover process heat demands. To support such distribution options new stakeholders like Ngas and energy companies, as well as industry, are needed in the future. As far as governmental support is concerned, it is, for example, important to promote and investigate alternative heat markets to support the development of new gas boosters and to provide funding for initial analysis of the possibilities for implementing biogas facilities within local communities, all of which would support a further development of the biogas sector.*

Keywords— **Biogas, Combined heat and power (CHP), Denmark, district heating, heat markets, renewable energy.**

1. INTRODUCTION

There are currently 21 centralized biogas CHP plans in Denmark that receive livestock manure from several connected farms, primarily from pig and dairy cow farmers, as well as organic waste from industry and households to increase the gas production. Denmark also host approximately 45 farm biogas plants, which are located at a single farm and most often based on manure from a large stock of slaughtered pigs. Apart from this several biogas plants are operated on wastewater treatment plants, digesting sludge from the cleaning process. Hence, 58 biogas plants are connected to water treatment, 26 to utilization of landfill gas, and finally six industrial plants digesting sludge from, for example, medical and food manufacturing industries [1] & [2].

The gas is primarily used for CHP production, providing electricity to the grid and district heating to local communities. Biogas distributed on the natural gas (Ngas) network, by means of upgraded biogas, is still in its infancy in Denmark. Only one plant injects small amounts of upgraded biogas from a wastewater treatment facility, and another is operated as a pilot plant on a centralized biogas plant. The total production of biogas, mainly from centralized biogas plants, equals four PJ, or around 0.5 % of the total national energy consumption [1].

The annual production of livestock manure in Denmark accounts for 30 m. tons, but only six per cent of this amount is digested. The political focus on the biogas technology has been strengthened in recent years, and the government's targets for biogas have increased.

Today, the political target is to digest 50 % of the manure before 2020, which will contribute to an energy production of approximately 20 PJ [3]. This will provide a reduction in CO_2 emissions corresponding to approximately 580,000 tonnes annually [1].

Apart from the CO_2 emission reductions there are several other important environmental benefits associated with biogas, which emphasize the relevance of biogas as a valuable technology in a forthcoming transition of the energy supply. Production of biogas has, for instance, the ability to transform organic waste materials into valuable resources for society, by utilizing waste from animal livestock or organic waste from household, industry etc. The generation of waste is a large problem globally, and challenges with overproduction of organic wastes from industry, agriculture and household, are commonly observed [4].

Centralized biogas plants digest agricultural such as: Rape oil and seed, soybean, corn residues, fruit and vegetables residues this emphasizes the plants capability to re-circulate nutrients. Furthermore, the following industrial waste products are often applied to the plants: Fish residues, different waste from food industries, flotation grease, and intestinal contents from slaughterhouses. Again, other plants also digest organic source separated food waste from kitchens and canteens, from e.g. Copenhagen. The organic waste is hence re-cycled in the biogas plant together with manure etc. The biogas technology can thus assist in re-circulate nutrients from organic waste back to the soil, instead of being - in a Danish context - mainly incinerated, or dumped in landfills which are commonly applied in several

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European countries and elsewhere. Thus, the volume of the total waste will decrease, just like nutrients will be re-cycled, which can increase the fertility of the soil [2].

Nutrients in the fertilizer will also be more directly assessable for the farm crops, as the chemical form shifts to ammonium when the manure has been digested. An 80 % uptake of nitrogen is observed for digested manure, as opposed to 70 % for untreated manure. This means that the risk of nutrient pollution to rivers, lakes and ground water reservoirs are reduced. Also, unpleasant odors connected with distribution of manure on the fields decrease by as much as 30 %. As the digested manure receives a declaration of its content of nitrogen, phosphorous and potassium, it enhances the options for controlling and regulating the distribution of nutrients on farmland even further [5].

The manure also undergoes a sanitation process in the reactor tank meaning that pathogen organisms, germ and seeds are eliminated, which reduces the risk of spreading diseases between farms. The degradation of hazardous substances like for instance PAH (polyaromatic hydrocarbons) - which increase the risk of cancer, is genotoxic, and can damage fetuses and the ability to have children - can also be significant reduced by the biogas process [6]. Almost 100 % degradation of such substances was found through experiments made on centralized biogas plants in Denmark [5].

2. PROBLEM AREA & RESEARCH QUESTION

In order to harvest the many benefits associate with biogas, as described above, it is important that the technology is disseminated throughout Denmark; and more extensively on Zealand. This paper therefore presents and discusses how the utilization of biogas can be enhanced within municipalities on Zealand, which lack manure potentials compared to mainland Jutland. The quantity of manure is thus lower and the catchment area larger, due to longer distance between farms of relevant size. The existing distribution options for biogas have so far been to establish 1) co-owned centralized biogas plants for supplying electricity to the grid and district heating to a local heat market (households), as well as 2) smaller farm biogas plants supplying electricity to the grid and heat to farmhouse and stables.

The main stakeholders in the biogas development have primarily been farmers wanting to treat their livestock manure in biogas plants, to receive back a more valuable fertilizer for their crops. The biogas sector has, however, not evolved for several years and barriers like lack of financial loan opportunities, low profitability, difficulties in locating large centralized biogas plants, and lack of gas boosters (organic waste) enhancing the gas yield, has hampered a further development.

Thus, alternative distribution options and inclusion of new stakeholders in the biogas development could be beneficial. This, in combination with enhanced governmental framework conditions, could push the biogas sector forward. But which new distribution options can be identifies for biogas and which new stakeholders could be included in the biogas development? And how can the Danish government enhance the framework conditions for biogas to support such new distribution options? Thus, the following research question is posed:

How can dissemination of the biogas technology be enhanced on Zealand, and how can new stakeholders and governmental support move the biogas sector forward?

3. METHODOLOGY

First we provide an overview of the biogas distribution options by looking at alternative ways of using the biogas produced; e.g. for distribution of high and low temperature process heat to industry, or for the upgrade to Ngas standard to be supplied on the gas network or used for transportation purposes. An option could, for example, be to distribute the energy as non-upgraded city gas to households, or distribute it in separate pipes by means of a locally established gas network to e.g. industry. Distribution of traditional district heating to new heat markets, identified within local communities, could also be an opportunity.

Second, we present the case studies conducted on Zealand to illustrate new distribution options. We will exemplify these distribution options taking our point of departure in three case studies. Each case will thus be utilized to examine several different distribution options, followed by a specific choice in the context examined, and an outline of the selected plant concept including its benefits, etc. Third, the emphasis is put on new stakeholders and their future role in the biogas sector. Finally, we suggest how to enhance the governmental framework conditions for biogas to promote the dissemination of the new distribution options proposed.

4. BIOGAS DISTRIBUTION OPTIONS

Figure 1 below depicts the distribution options for biogas emphasized during this research. In the section to follow we will provide examples of some of the distribution options provided in the figure.

Heat & gas supply

Local district heating network:

Existing centralized biogas CHP plants typically distribute heat to a local market of heat consumers by means of district heating. The size of the market can vary greatly from a few hundred customers to several thousand dependent on whether the district heating network is a smaller local network, or connected to a larger conventional network in the region. The plants are often established with municipal loan guaranties, due to their contribution to the municipal heat supply. All centralized biogas CHP plants in Denmark are established as conventional plants, and thus not as organic plants. In some areas the concentration of organic farms are relatively high, among others on Zealand, and it is therefore interesting to focus on the options for implementing an organic centralized plant to provide organic crop farmers with fertilizer.

Another challenge is that existing biogas CHP plants cannot allocate all heat produced during summer periods, as the demand for primarily space-heating decreases.

Newer the less, analysis show, that it is economically feasible to utilize biogas for supply of CHP in local communities if the demand for heat is high. By contrast, it is economically feasible to utilize the share of biogas - not being supplied as CHP locally - for upgrading to Ngas if the local heat demand is limited [7]. Thus, if alternative summer and winter markets for distribution of heat could be identified, it would be beneficial for the economy of the plants, and would increase the overall resource efficiency. If not, upgrading to Ngas networks could be an opportunity.

Local biogas network:

Direct supply of non-upgraded biogas e.g. to industrial and residential areas by means of local biogas networks is an option for expanding the distribution of biogas in the future. The location of especially industrial areas - due to the likeliness of a stable annual heat demand as oppose to households - can be coordinated with the location of existing biogas plants or the location of new plants. Thus, biogas can supply energy to such areas through a local biogas network, where opportunities for extending the conventional district heating network, or the implementation of individual renewable energy solutions, is not an option.

Such a network of non-upgraded biogas to local heat consumers is not yet applied in Denmark. But currently, a network of gas pipes for non-upgraded biogas for CHP production is being established in Ringkøbing-Skjern Municipality. From several smaller livestock farms the gas will be piped to a larger Ngas CHP plant in the area, distributing CHP to the local community (see more on alternative biogas designs etc. in [2]). Moreover, a gas pipe for non-upgraded biogas will be established to Arla (diary company), which uses large quantities of Ngas in their production of milk powder, which will be converted to biogas [8].

Ngas CHP Plant

Existing Ngas CHP Plant:

Biogas is also supplied to (motor-engine) Ngas CHP plants in which the gas is combusted for electricity and heat production. The heat is thus distributed by means of a larger conventional district heating network, supplying a greater area or region with heat. In coming years many Ngas CHP plants will convert to solar energy or biomass such as wood pellets etc., as the cost of Ngas will increase, due to changes in taxes put on fossil fuel utilization. It is therefore possible to substitute the use of Ngas with biogas within existing Ngas CHP plants.

The total efficiency of Ngas CHP plants and biogas CHP plants are highest on the first, as they can adjust the heat production to the heat demand and vary the electricity production, due to the flexibility of the Ngas system. On centralized biogas CHP plants the efficiency are hence lower, due to heat losses during summer periods where the local heat market is limited. Due to a constant supply of manure from livestock farms, which are only reduced by 15-20 % during summer periods, the flexibility on biogas CHP plants are lower thus and surplus energy (heat) is therefore produced [7].

New Ngas CHP Plant:

In areas where the utilization of Ngas and an extension of the conventional district heating network is not an option, new biomass fuelled CHP plants could be implemented, receiving gas from nearby biogas facilities. New biomass fuelled CHP plants will face the same problems with lack of heat markets, as described above, unless they supply energy to the Ngas network. If syngas from gasification of biomass and upgraded biogas are combusted on the plant, they will be capable of achieving the same flexibility as fuelled by Ngas only.

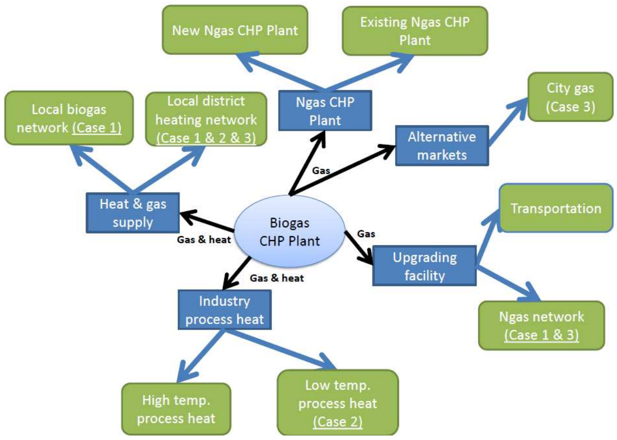

Fig.1. Biogas distribution options and case focuses.

Alternative markets

City gas:

The utilization of biogas from animal manure etc. for distribution as city gas is not yet applied within Danish municipalities, but could be a future supplement to city gas coming from Ngas. Supplied as city gas, there is no need to upgrade the biogas to Ngas standards, as the city gas is thin (49 % Ngas and 51 % atmospheric air). Up to 30 % biogas can be added without technical problems in the households, like the flame stopping, which is caused by a high content of CO_2 in the biogas.

The gas quality is, however, not only determined by the content of methane, as the biogas will have to be cleaned for hydrogen sulfide and ammonia before mixing with Ngas [9]. The distribution of biogas supplied as city gas in Denmark is limited and only municipalities in Aalborg and Copenhagen offer this opportunity to gas costumers’. Here, the biogas is produced on wastewater treatment plants digesting sludge. There is hence a potential market for distributing biogas to the city gas distribution networks within municipalities on Zealand utilizing the already established network.

Upgrading facility

Transport:

Biogas for transportation is still in its infancy in Denmark compared to for example Sweden and currently there are only three Ngas stations for vehicles to fill their tanks with conventional gas. A large municipal or company vehicle fleet could however motivate private stakeholders to become interested in providing upgraded and pressurized biogas for transportation purposes; e.g. the municipality of Copenhagen or a large private taxi company. This could potentially create a market for biogas or a mix of Ngas and biogas, as opposed to conventional gas.

The well-distributed gas network in Denmark (see below) can thus provide the basis for an infrastructure of gas stations throughout the country [10] & [11]. Currently, however, there are no gas stations that provide biogas in Denmark, but only three Ngas stations recently established. However, within the next year or so a few biogas stations, will eventually be introduced by private stakeholders like energy companies [11].

Ngas network:

As seen, biogas can also be upgraded and cleaned to Ngas standards for distribution on the widespread Ngas network, distributing energy to household and industry, etc. To achieve Ngas standards biogas has to be cleaned for CO_2 and pressurized, etc. Today, biogas can be certified by the governmental organization in Denmark named 'Energinet.dk', who guaranties that the gas substitutes fossil fuel like Ngas and thus result in supply of CO_2 neutral energy. The certification makes it possible for the energy consumers to track down the origin of the biogas all along the supply chain. So far only one Danish energy company, DONG energy, produces and distributes upgraded biogas to the Ngas network [11].

The challenge regarding upgrading for transportation and distribution on the Ngas network is however the price, which ad up to 0.5-1.00 DKK (0.067-0.13 €) to the total production price. Thus, only where local markets for biogas CHP cannot be identified - or surplus energy is produced - it would be favorable to upgrade the biogas for distribution to a larger market.

Industry process heat

High and low temperature process heat:

Another future opportunity for utilizing biogas within municipalities on Zealand is to substitute the use of fossil fuels like Ngas or coal etc. in industrial manufacturing. Thus, a large industrial application using e.g. Ngas for high temperature process heat, could thus convert to the use of non-upgraded biogas substituting Ngas. The energy produced on biogas CHP plants could also be supplied as district heating to cover lower temperature process heat demands, also here substituting the use of fossil fuel for process heat generation.

It would be beneficial to identify local industrial heat markets as future distribution option for biogas. This could be the industry that uses heat, primarily during summer periods, like in some agricultural or horticultural businesses. It could also be industries with steadier annual heat consumption, complying better with the production of gas on biogas CHP plants. In this way larger markets for heat will be available all year round and also during summer periods.

5. BIOGAS STAKEHOLDERS

So far the Danish biogas development has been centered around farmers, who has been the main drivers in implementing the technology, supported economically by municipalities through cheap public loans (municipal loan guarantees with an interest rate of four per cent p.a.). Some municipalities are however reluctant to provide such loans, due to bad experiences with failed biogas projects, e.g. Nysted biogas plant. It is, however, important that this 'Danish-model' of implementing biogas plants, which distributes heat in local communities, supported by the municipal heat planning, is continued.

If the dissemination of the biogas technology and the use of biogas in the energy system should expand further, new stakeholders are however needed in the future. Private companies, e.g. Ngas companies, should be active in upgrading biogas for distribution of gas in the Ngas network, and to provide biogas for transportation purposes. Ngas companies are therefore also likely to actually establish biogas plants to enable ownership of the entire production chain. This development is in it infancy, but already seen on Funen, where an Ngas company has engaged in the implementation of a biogas plant in Jutland.

Manufacturing industries too should look for opportunities for converting fossil fuel fed boilers with biogas for process heat generation as seen in the case of Arla producing milk-powder in Ringkøbing-Skjern. This could be through the supply of biogas from a nearby biogas plant, or by implementing a biogas plant at the company itself digesting organic waste, e.g. from slaughterhouses, sugar factories, breweries and other types of beverage and food manufacturing industries.

The existing pattern of ownership within the Danish biogas sector - with privately co-owned centralized as well as farm biogas plants - will thus be challenged in the future, if a larger market for and distribution of biogas should be achieved. This also includes the public sector (municipalities), where alternative ways of distributing biogas should be provided in the future. The use of biogas as city gas is an example for the future, as well as distribution of public supported non-upgraded biogas in separate biogas networks for heat purposes. In the following section we will exemplify some of these distribution options previous outlined, by means of three case studies conducted on Zealand.

6. BRIEF PRESENTATION OF CASES

Data used in the following section are from the 2014 research report conducted by the authors titled: "Opportunity analysis of biogas distribution options on Zealand & The future role of municipalities in promoting biogas" (see ref. [12]).

Case 1: Organic biogas plant in Lejre municipality

Distribution options:

As indicated in Figure 1 there are three distribution options for Case 1. The options are as follows: 1) the use of non-upgraded biogas in a local gas network supplying households with biogas for heating purposes, and 2) the production of CHP in a gas engine for distribution of electricity and district heating, or heat only by means of a heat boiler, and 3) supply of biogas to an upgrading facility that upgrades it to Ngas standards, and thus supply the biogas to the existing Ngas network.

Choice of energy supply:

A minimum of 5 m. m³ biogas should be produced on an annual basis to deal with the investments in an upgrading facility. As the suggested plant only produces 3.7 m. m³ biogas annually, it is not considered a feasible solution in this case. Distribution of non-upgraded biogas to households through a local biogas networks requires a steady heat market all year round, as it is problematic - both technically and economically - to store the biogas over longer periods.

The supply of non-upgraded biogas directly through a local biogas network is however hampered by lack of a *sufficient* heat market in the case area. The actual heat demand in Kirke Hyllinge is 9,500 MWh of Ngas, but the generated biogas will provide 22,900 MWh heat only. Thus, there is a surplus of biogas for the heat market in Kirke Hyllinge. A traditional plant concept where the biogas is converted to heat *and* power by means of a gas engine is therefore selected in this specific case, leading to a heat production of 11,600 MWh and a power output of 8,800 MWh annually. The proposed supply of energy is illustrated in Figure 2 below.

Plant concept & benefits:

- The plant concept is a traditional CHP plant with supply of electricity and heat, and
- Is operated as base-load for a more favorable plant profitability, thus
- The energy needs of the local community is matched with the capacity of the technology
- The biogas plant substitutes the use of Ngas in the local community
- The plant facilitates an increase in organic farming in the local community on Zealand
- The use of ray-grass are suggested, but several other types of local gas boosters are identified like industrial waste and agricultural residues
- The fertilizer (digestate) has high value for farmers due to nitrogen content and is easy distributed on farmland.

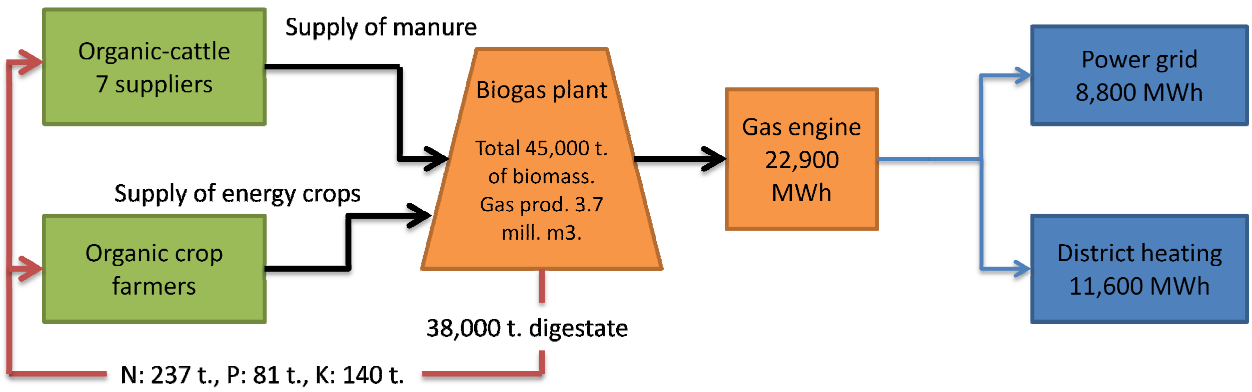

Fig.2. Biogas plant in Kirke Hyllinge.

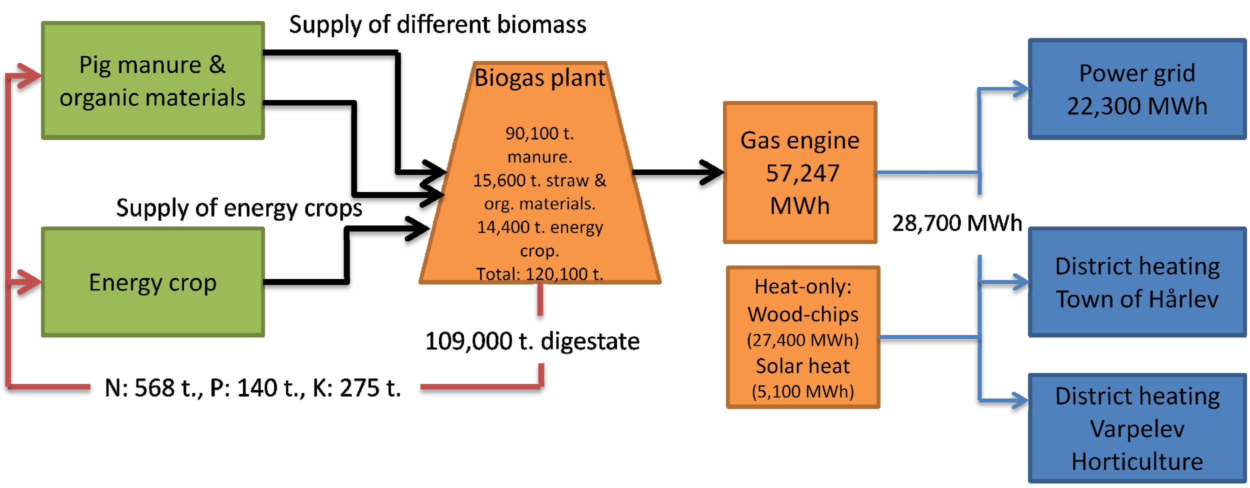

Fig.3. Biogas plant in Hårlev / Varpelev-horticulture.

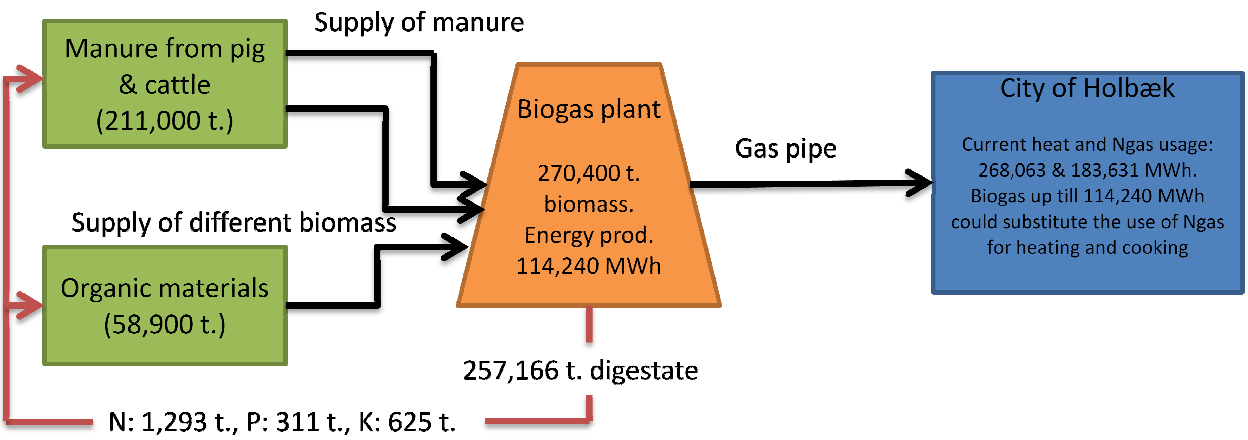

Fig.4. Biogas plant in Tuse.

Case 2: Biogas plant in the towns of Varpelev - Hårlev

Distribution options:

There are two distribution options for Case 2. The options are as follows: 1) production of CHP by means of a gas engine distributing power to the grid and district heating through an existing or new district heating network, or 2) supply of energy to a local industry substituting on-site consumption of fossil fuels for low temperature process heat.

Choice of energy supply:

The energy production is estimated as being sufficient to provide energy to both cases examined; to a district heating network supplying heat to citizens of Hårlev *and* to substitute the use of a coal fired boiler for heat production at Varpelev horticulture. The biogas plant will produce 22,300 MWh electricity distributed on the power grid and 28,700 MWh heat, which partly will be used for district heating supplied to the town of Hårlev (primarily during winter), and partly for low temperature process heat to Varpelev horticulture (during summer). They produce tomatoes and cucumbers in greenhouses. The company will additionally produce heat from solar heat collectors and from combustion of wood chips, of which some of this heat also will be supplied to Hårlev, by means of district heating network from the company, when surplus occur. The energy system is depicted in Figure 3.

Plant concept & benefits:

- The plant is a traditional CHP plant with supply of electricity and heat, where
- The heat market is matched to the local context, and
- Alternative heat markets provided by a horticulture requiring heat in summer periods, thus via
- Supply of low temperature process heat to industry
- The biogas plant is operated as base-load, and
- Substitute the use of Ngas and coal in the local community and industry
- Straw and grass from grass seeds are identified in the local community and could be supplied as gas boosters
- A valuable fertilizer is produced like in the previously case.

Case 3: Biogas plant in the town of Tuse

Distribution options:

There are three distribution options for Case 3. The options are as follows: 1) the use of biogas for CHP production with supply of electricity to the grid and heat by means of district heating, or 2) distribution of biogas as city gas substituting Ngas, or 3) upgrade biogas to Ngas standards for supply in the gas network substituting Ngas.

Choice of energy supply:

The large city near Tuse - named Holbæk - is currently supplied by Ngas, which is used for heating up households in individual installations (heat boilers). The high production of biogas from the suggested plant, which totals 17.7 m. m³, makes it economic feasible to upgrade it and distribute the gas - through a gas pipe - to the city of Holbæk, where the energy will cover half of the existing heat demand based on Ngas. Alternatively, and less cost full, the biogas can simply be cleaned for hydrogen sulfide and ammonia before mixed with Ngas, and then distributed as city gas for cooking in Holbæk. Both options are therefore viable in the case of Holbæk, and they provide opportunities for achieving high CO_2 emission reductions.

Even though a part of the biogas - with a future expansion of the supply of district heating - could be utilized for district heating purposes also, the immediate selected distribution options are here to upgrade the biogas to Ngas standards for heating purposes, and to clean and distribute the biogas as city gas. When the district heating network is expanded furthermore, energy from biogas can be supplied this way. Figure 4 above illustrates the proposed energy supply system.

Plant concept & benefits:

- Production of city gas or/and upgraded gas to the Ngas system is proposed in this case, due to lack of local heat markets, but
- Due to an expansion of the district heating system in the future, it will be possible to
- Supply district heating to households in winter, and
- Upgrade biogas to the Ngas network during summer

periods

- The flexibility of biogas as energy carrier is thus used to facilitate a transition period from Ngas to district heating in the local community
- Biomass boosters like deep litter, straw and grasses are identified in the local community, and if especially the latter are applied,
- A valuable fertilizer is produced due to the high content of nitrogen.

Case discussion and highlights

Besides the production of energy on biogas CHP's plants - supplying energy to local communities as electricity to the grid and district heating to local communities, substituting the use of Ngas etc. - the cases also highlights the opportunity of identifying new types of heat markets. The cases show that it *is* possible to identify alternative heat markets that are vital for the plant profitability. This was shown by the distribution of district heating to a horticulture company requiring heat during summer periods, where supply of low temperature process heat (district heating) was suggested. Such markets are hence assessable and should be identified more thoroughly in the future. In situations where alternative summer heat markets are not available - and surplus energy occur - it would be possible to upgrade the biogas to the Ngas network, and hence supply the energy to the national network.

In addition to the heat markets identified above, we suggest the following alternative heat markets being supplied by heat from biogas plants during summer periods: Other types of agricultural business, like sugar industries using large amounts of heat during summer periods when processing sugar beet. The heat could also be used during summer periods for drying fractions of municipal waste. Thus, fractions for incineration - not being digestible - could be dried during summer months and incinerated during winter periods, and the wet fractions however immediately supplied to biogas plants.

Alternatively, the heat could be supplied to an outside swimming pools requiring heat to provide a comfortable water temperature. On an annual basis, but to a minor extent, the heat could also be supplied as hot water to washing machines and dishwashers in households that all rely on electricity to produce hot water. This could instead be supplied by means of district heating. In this way the energy efficiency will increase, and the machines will avoid heating elements that are attacked by calcification.

The cases also illustrated that it is possible to match the local energy demand with the plant capacity, and that the biogas plant should be operated as base-load in order to achieve a favorable plant profitability. If peak heat demand is required, it should be covered by an alternative energy source, for example a small wood fuelled boiler or solar energy. All cases show that grasses can be applied to the biogas plant, hence avoiding the use of food products (maize and beet which are traditional gas boosters) to boost the gas production.

Emphasis was put on ray-grass, but clover grass and lucerne could also be an option. These grasses provide a high gas yield, and at the same time they contain large amounts of nitrogen, which is favorable when applying it on farmland later on as digested fertilizer. Due to the dry matter content obtained (below 10-12 % TS), the actual distribution of the fertilizer is easy. Besides the option and benefits of using grasses, the cases also show that manure from mink and deep litter can be utilized, and that waste from agriculture, like straw, as well as industrial waste are assessable; the latter however in limited amounts.

All cases showed environmental benefits as far as CO_2 emission reductions and the production of valuable fertilizer. The case of Tuse however also prove that a centralized biogas plant based on organic farming can support the development of organic farms on Zealand even more, and thus assist in limiting the overall amount of pesticides, fungicides etc. used in Lejre municipality. Currently, there is lack of organic manure that hampers a further development of organic farming on Zealand.

The cases further proved that new stakeholders should engage in biogas development, as the need to upgrade biogas will occur in the future as distribution option. Where the local heat market is too small or already saturated, etc., it is important to be able to upgrade to the Ngas system. The supply of non-upgraded biogas as city gas was also identified as a distribution option, requiring new stakeholders to engage. Thus, Ngas companies and other energy companies could play a role in providing such upgrading services.

7. FRAMEWORK CONDITIONS

The newly increased construction grant is most beneficial for the biogas sector that faces very high construction costs, hampering favourable plant profitability. We, however, suggest that the construction grant - when not fully utilized, as is currently happening - should be used to provide cheap municipal loan guarantees. The expected support to biogas used within industry and for transportation purposes is also very beneficial. Support for biogas used in industry is highly relevant, as it facilitates the development of local heat markets. Thus, these framework conditions support the new distribution options outlined.

We further propose that the 10 and 26 DKK/GJ (1.33 and 3.46 €) become index-regulated, and thus follow the general economic trend. Otherwise, the operating support will not be worth much due to the relatively high inflation currently seen. The electricity price should also follow the Ngas price, as the increasing gas prices eventually will de-value the price of electricity achieved at the plants. In addition to the suggestion above, the following initiatives could be provided by the government to support the biogas sector:

The government could also provide financial support for initial surveys and analysis of possibilities for implementing biogas plants in local communities. This type of support is for instance provided for windmills and has proved beneficial. In addition to this, financial support for implementing local biogas networks for non-upgraded biogas could be very useful. The biogas can thus supply energy to industry and households phasing out Ngas or other types of individual solutions based on fossil fuels. This will support new heat markets for biogas within local communities, and thus enhance the profitability of the biogas plants implemented. We further suggest that the government support a mapping of alternative heat markets within the Danish communities, which could be conducted by municipalities, and result in a more local and non-upgraded distribution and consumption of the energy where possible.

Where this is not possible, the Danish government should require decentralized Ngas CHP plants to be obliged to use and thus purchase biogas from a nearby biogas plant. This would create a larger market for biogas, but still, however, be connected to a seasonal need (reduced demand during summer periods). Thus, the expected governmental support related to upgrading of biogas to Ngas standard - to be utilized within industry and for transportation purposes etc. - is therefore also important for creating additional markets.

Besides carrots and sticks, the government may also engage municipalities on a voluntary basis in the dissemination of the biogas technology, by elaborating on its benefits. Much more must be done in order to provide and distribute knowledge of the effects of biogas within local communities. Thus, the biogas sector should not only be promoted by rules, regulation and economic support etc., but definitely also by the many benefits associated with the technology such as how it benefits the climate, water resources, and the benefits obtained by farmers through better crop nutrients etc. Local short and long term jobs are also created and new taxpayers provided.

We suggest that governmental officials and green organisations, together with the biogas branch organisation, including farmers etc., provide seminars and conferences conducted in each region or within specific municipalities where the potential for biogas is very high. Courses should be provided to local politicians and planners within municipalities and biogas networks across municipal boarders should be established. Visits to biogas plants and study materials can be disseminated, and people in the branch can tell the ‘good story’.

8. CONCLUSION

The Danish biogas sector is currently hampered by a technology track focuses on large scale biogas CHP plants distributing electricity and heat to local markets, and the fact that municipalities are reluctant to provide municipal loan guaranties, which limits new plants being implemented. The main purpose of implementing biogas plants has also shifted, challenging the technology track. Previously, the importance for farmers engaging in biogas was primarily to receive back digested manure providing a good quality fertilizer [13]. Today, however, new priorities have emerged where farmers and other potential investors would like to gain a profit from their investments in biogas. In order for this sector to move forward new stakeholders should therefore be included and new ways of using and distributing biogas should be emphasised. New framework conditions provided by e.g. government should further support the dissemination of the biogas technology.

Departing from the case studies conducted, we argue that local biogas CHP plants should have first priority when selecting distribution options if a sufficient (summer and winter) market for heat can be identified, as the energy will be produced and consumed locally, followed by high energy efficiency and environmental benefits. It is, however, not obvious that all the energy can be distributed locally by means of CHP, due to long heat market distances or due to a saturated heat market. In such situations it is beneficial to look at other distribution options, as mentioned above. Distribution of non-upgraded biogas in separate gas networks could be an option to e.g. households, but most beneficially to industry for process heat purposes.

The cases highlight that upgrading of biogas to the Ngas network during summer periods could be a new distribution option if local heat markets cannot be found. Greenhouses requiring heat during summer periods and sugar factories processing beet during the warm summer, etc., can for instance provide alternative heat markets. There are, however, no unified solutions and each context will have to be exanimated separately in collaboration with e.g. neighbor municipalities to find the optimal solution.

The government has enhanced the economic support to biogas compared to previously, but there is still a need to enhance the framework conditions for biogas in various ways, e.g. index-regulate the economic support (the 1.33 and 3.46 €/GJ), and have the electricity price follow the Ngas price. The support to biogas within industry and for transportation purposes is highly relevant for disseminating the new distribution options proposed in this research. The government should also, very importantly, assist in providing alternative gas boosters, preferably grasses with multiple benefits for the natural environment, which can also support the foundation for organic farming. The government could assist in planning how such resources should be harvested and shared between the regions in Denmark to avoid unfavourable competition. To oblige CHP plants to utilize biogas from nearby biogas plants in their fuel mix, can also support the biogas sector.

We further suggest that the government fund initial analysis of opportunities for implementing biogas within municipalities - equal to the fund provided for wind energy - and support the implementation of local gas networks for non-upgraded biogas, as well as mapping of alternative heat markets within Danish municipalities. Pivotal is also that the government provide knowledge to municipalities about the benefits of biogas, focusing on climate, nutrients, water resources and job creation, etc. New stakeholders in the biogas sector could be industry, Ngas companies and other energy companies providing upgrading facilities for supply of biogas on the Ngas network, or for use within the transportation sector.

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An Experimental Study of Lignocellulosic (Oil Palm Residues) Pretreatments for Cellulose Extraction

Tanakorn Wongwuttanasatian*, Amnat Suksri, and Kittichai Jookjantra

Abstract— *This research aimed to investigate the effectiveness of the pretreatments for cellulose extraction of oil palm residues. Steam explosion method and acid or alkaline digestion based on detergent analysis method were the pretreatments used in this research. Four types of oil palm residues were considered: oil palm seed meal, oil palm meal, oil palm leaf, and oil palm trunk. The effectiveness of the two pretreatments was determined by measuring the amounts of percent cellulose extracted from all four types of oil palm residues. The cases steam explosion pretreatment provided higher percent cellulose than the acid or alkaline digestion cases did for all cases. Oil palm seed meal showed the highest percent cellulose extracted compared to those of the other three oil palm residues for both pretreatments.*

Keywords— **Oil palm, residues, steam explosion, detergent analysis.**

1. INTRODUCTION

Ethanol is an alternative fuel that has gained a lot of attention due to its cleaner energy compared to gasoline. In Thailand, ethanol production is mainly from sugar (cane and molasses) and starches (cassava, rice, and maize) [1]. The Ministry of Energy, Thailand had supported the ethanol production during 2008 to 2011 by targeting the annual production capacity of 3 million liters. However, the current ethanol production could only reach 2.95 million liters/year (1.76 million liters of molasses/year and 1.19 million liters of cassava/year) which is not enough capacity [2]. As a result, there is still a shortage of raw materials in the production of ethanol. The conversion of food crops to biomass energy crops also provides a risk to food security. One of the potential raw materials other than food is lignocellulosic materials [3]. Oil palm residues are lignocelluloses and usually in a form of waste from oil palm or biodiesel industry. Over the past several years, Thai government has encouraged farmers in the east and south of Thailand to cultivate oil palm [4]. In addition, oil palm trees are usually cut down after 25 years due to their inability to yield palm oil anymore, causing a lot of oil palm waste. Moreover, oil palm waste is normally disposed or incinerated, which offers a great threat to the environment. Apart from the abundance of oil palm residues, the preliminary study showed that dry oil palm had a proportion of cellulose up to 37.14 % which has a high potential to be a source of ethanol production [5].

In order to convert oil palm cellulose to ethanol, the structure of lignocelluloses must be digested by using pretreatment [6]. Umikalsom et al [7] examined the pretreatment of empty fruit bunch by soaking it in nitric acid (HNO_3) at a concentration of 0.5% by volume for 4 hours and then boiling it at 121 °C at a pressure of 15 lb for 5 minutes by using the steam sterilizer. The researchers found that the pretreatment provided 62.9±0.90% by weight of cellulose based on the empty fruit bunch that had 50.4±1.20% by weight of cellulose. Rashid et al [8] found that the pretreatment of oil palm stems by using sodium hydroxide at a concentration of 3% at 100 °C for 2 hours would result in an increase of 24.42% of cellulose. As a result, if oil palm residues, particularly oil palm trunk, are used as a renewable energy source to replace gasoline, this will reduce the shortage of raw materials in the production of ethanol, generate income to the oil palm farmers, and also enhance the country's competitiveness of renewable energy.

This paper aimed to study the effectiveness of two pretreatment methods: (1) steam explosion and (2) acid or alkaline digestion based on detergent analysis on four types of oil palm residues (oil palm seed meal, oil palm meal, oil palm leaf, and oil palm trunk). The amounts of cellulose of oil palm residues extracted from the two pretreatment methods were measured and compared to determine the effectiveness of each method.

2. EXPERIMENTAL METHODS

2.1 Materials preparation.

Four types of oil palm residues were considered in this paper: (1) oil palm trunk, (2) oil palm leaf, (3) oil palm meal, and (4) oil palm seed meal as shown in Fig. 1. These four oil palm residues were grounded and cut to have 0.20 mm to 2 mm in width and 10 mm to 20 mm in length. These oil palm residues were controlled to have humidity less than 100% by sun drying or baking. The dried oil palm residues were then chemically extracted to determine the percent amounts of cellulose, lignin, moisture, and ash.

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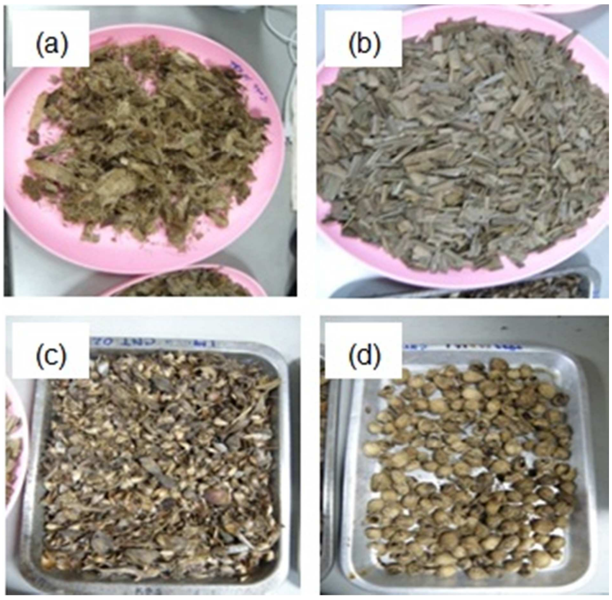

Fig. 1 Oil palm residues as the raw materials. (a) Oil palm trunk. (b) Oil palm leaf. (c) Oil palm meal. (d) Oil palm seed meal.

Fig 2. The oil palm residues after soaking in 0.08% diluted sulfuric acid for 8 hours (a) Oil palm trunk. (b) Oil palm leaf. (c) Oil palm meal. (d) Oil palm seed meal.

Fig 3. The steam explosion machine.

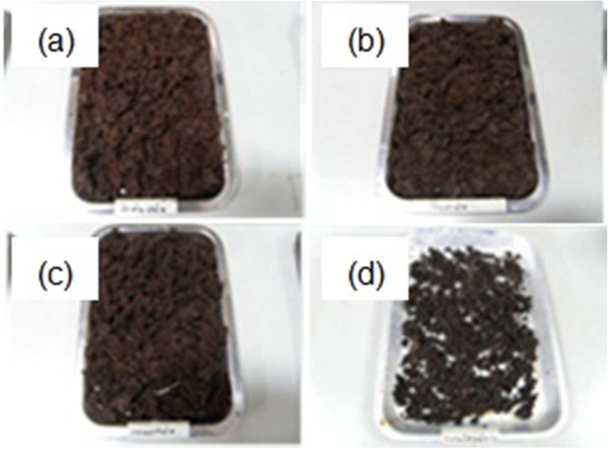

Fig 4. Digested residues after washed with hot water at 80 °C for 30 minutes (a) Oil palm trunk. (b) Oil palm leaf. (c) Oil palm meal. (d) Oil palm seed.

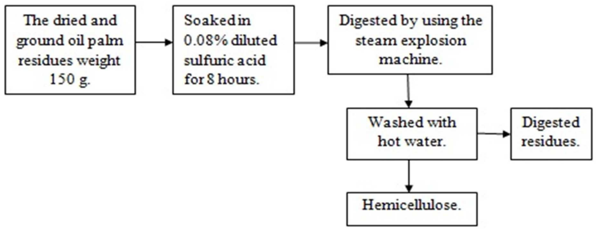

Fig 5. Procedure of digested residues with the steam explosion method.

2.2 Steam explosion pretreatment

The pretreatment by using steam explosion carried out in this paper was based on the work of Punsovon et al [5]. To begin the pretreatment, 150 g of the dried and ground oil palm residues obtained from the materials preparation (approximately 1 mm in width) was soaked in 0.08% diluted sulfuric acid for 8 hours. The Fig. 2 showed the oil palm residues after soaking. Then, the structure of these residues was digested by using the steam explosion machine (shown in Fig. 3) at 203 °C for 5 minutes. The digested residues were washed with hot water at 80 °C for 30 minutes to remove hemicelluloses as shown in Fig. 4. The ratio of digested residues per hot water was 1:10 (in 1 L of hot water). Then, the digested residues were dried and chemically extracted to determine the chemical compositions in accordance with TAPPI T203 om-88 [9]. The procedure of steam explosion pretreatment is illustrated in Fig. 5.

2.3. Acid or alkaline digestion based on detergent analysis pretreatment

The pretreatment by using acid or alkaline digestion based on detergent analysis carried out in this paper was based on the work of Goering et al [10] to begin the pretreatment, 150 g of the dried and ground oil palm residues obtained from the materials preparation (approximately 1 mm in width) were boiled with a neutral solution. Fig. 6 showed the procedure of wall cells analysis with detergents method. Then, Neutral Detergent Fiber (NDF) was analyzed to obtain percent

NDF as in Fig. 7. Afterward, the extracted NDF solution was boiled with an acid solution. Then, Acid Detergent Fiber (ADF) was analyzed to obtain percent ADF as in Fig. 8. Next, the extracted ADF solution was digested by using sulfuric acid (H_2SO_4) with a concentration of 72%. Then, the Acid Detergent Lignin (ADL) was analyzed to obtain percent ADL. Finally, the percent amount of cellulose was calculated by:

$$\text{Percent cellulose} = (\text{weight of ADF} - \text{weight of ADL}) / \text{weight of dried oil palm residues.} \quad (1)$$

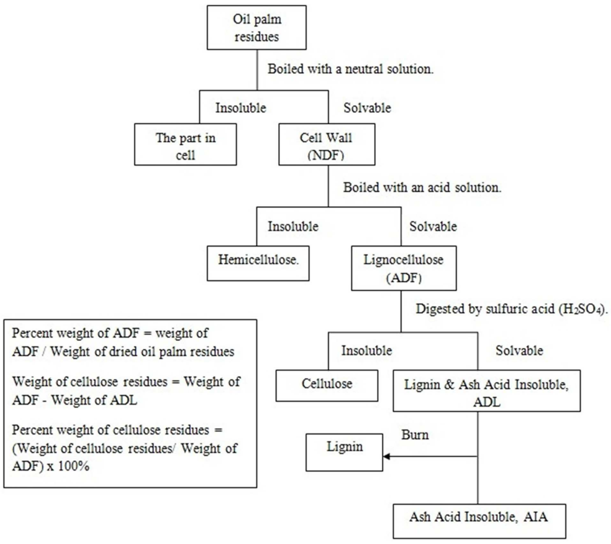

Fig. 6. Procedure of wall cells analysis with detergents method.

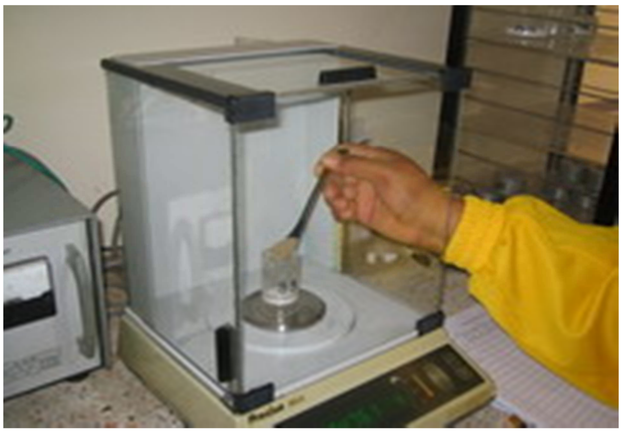

Fig 7. Analysis of % NDF as NDF testing method.

3. RESULTS

3.1 Chemical extraction of oil palm residues.

According to Table 1, the highest to lowest amounts of percent cellulose of oil palm residues prior to being pretreated were from oil palm trunk (29.98%), oil palm leaf (28.91%), oil palm meal (28.22%), and oil palm seed meal (28.15%), respectively.

Fig 8. Analysis of % ADF as ADF testing method.

Table 1. Results of chemical extraction of oil palm residues

Types of oil palm residues	Percent weight (%)			
	Cellulose	Lignin	Moisture	Ash
Oil palm seed meal	28.15	36.49	11.40±0.06	8.80±0.18
Oil palm meal	28.22	33.23	12.52±0.13	7.72±0.28
Oil palm leaf	28.91	45.22	14.57±0.27	10.62±0.16
Oil palm trunk	29.98	33.43	10.78±0.09	8.32±0.28

3.2 Results of steam explosion pretreatment.

According to Table 2, the highest to lowest amounts of percent cellulose of oil palm residues after the steam explosion pretreatment were from oil palm seed meal (34.72%), oil palm trunk (19.55%), oil palm meal (18.96%), and oil palm leaf (28.91%), respectively. Even though oil palm seed meal provided the highest percent cellulose, its structure was the strongest, which was difficult for digestion.

Table 2. The differences of percent cellulose before and after the steam explosion pretreatment

Types of oil palm residues	Before pretreatment	After pretreatment	Difference of percent cellulose before and after pretreatment
	Percent cellulose (%)	Percent cellulose (%)	
Oil palm seed meal	28.15	34.72	6.57% increase
Oil palm meal	28.22	18.96	9.26% decrease
Oil palm leaf	28.91	13.35	15.56% decrease
Oil palm trunk	29.98	19.55	10.43% decrease

3.3 Results of acid or alkaline digestion based on detergent analysis pretreatment

According to Table 3, the highest to lowest amounts of percent cellulose after the acid or alkaline digestion based on detergent analysis pretreatment were from oil palm seed meal (28.17%), oil palm meal (16.20%), oil palm trunk (15.96%), and oil palm leaf (12.75%), respectively. Similar to the results obtained from the steam explosion pretreatment, oil palm seed meal provided the highest percent cellulose but its structure was the strongest, which was difficult for digestion.

Table 3. The differences of percent cellulose before and after the acid or alkaline digestion based on detergent analysis pretreatment

Types of oil palm residues	Before pretreatment	After pretreatment	Difference of percent cellulose before and after pretreatment
	Percent cellulose (%)	Percent cellulose (%)	
Oil palm seed meal	28.15	28.17	0.02% increase
Oil palm meal	28.22	16.20	12.02% decrease
Oil palm leaf	28.91	12.75	16.16% decrease
Oil palm trunk	29.98	15.96	14.02% decrease

4. DISCUSSION AND CONCLUSION

This paper investigated the effectiveness of the two pretreatment methods: (1) steam explosion, and (2) acid or alkaline digestion based on detergent analysis. The effectiveness was determined by measuring the percent cellulose of four types of oil palm residues: (1) oil palm seed meal, (2) oil palm meal, (3) oil palm leaf, and (4) oil palm trunk before and after the pretreatments.

The results showed that most of the amounts of percent cellulose (oil palm meal, oil palm leaf, and oil palm trunk) were decreased after the pretreatments. This was due to the fact that the operating conditions for cellulose extraction used in each pretreatment were not optimized. However, the pretreatments of oil palm seed meal provided an increase in percent cellulose, which was due to the strength of oil palm seed meal and the effectiveness of hemicellulose removal. The steam explosion pretreatment provided higher amounts of percent cellulose than those of using the acid or alkaline digestion based on detergent analysis pretreatment. This was mainly due to the more effective hemicelluloses removal of the steam explosion pretreatment.

The authors also found that the steam explosion pretreatment should be used for strong oil palm residues and the acid or alkaline digestion based on detergent analysis pretreatment should be used for soft oil palm residues. Nevertheless, the operating conditions for cellulose digestion of each pretreatment should be optimized for each type of oil palm residue.

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NOMENCLATURE

ADF	The Acid Detergent Fiber
ADL	The Acid Detergent Lignin
AIA	The Ash Acid Insoluble
NDF	The Neutral Detergent Fiber

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Application of Heat Insulation Solar Glass for Glass Buildings

Tran Thi Bich Quyen*, Chin-Huai Young, Bui Le Anh Tuan, and Ching-Sung Hsu

Abstract— *To enhance electrical energy production and improve heat insulation of photovoltaic modules (original solar glass module), a simple method for installation and generation of heat insulation solar glass (HISG) modules from traditional transparent PV modules (original solar glass modules) using heat insulation materials, improving functions such as power generation, heat insulation, energy saving and greenhouse gas reducing. Interest in photovoltaics (PV) integration into buildings, as well as heat insulation solar glass (HISG) be used as curtain walls on the buildings has been developed, where the HISG curtain walls play the role of building exterior components as an integral part of buildings as well as of producing electricity and providing functions such as heat insulation and self-cleaning. Two experimental houses used normal glass and HISG as curtain walls on the Ordinary house and the HISG house were constructed in this study. Results show that the illuminative penetration on HISG curtain was quietly high with efficiency of 32%, block UV-rays to 100%, low solar radiation 40% as compared to normal glass curtain wall (~97%), greatly enhanced indoor lighting ~29.4% and high heat insulation efficiency ~28.2% as compared to normal glass curtain wall on the Ordinary house. In addition, the energy-saving efficiency of the HISG house for heating and cooling were greatly improved respective to ~40% and 48% for comparisons to the Ordinary house, and the power generation of HISG curtain wall on the HISG house was achieved 2.63 kWh of electricity per day. Our work offers a low-cost route to the application of HISG modules able to be used for monitoring progression of the greenhouse gas reduction, as well as evaluating their energy efficiency on buildings in the green buildings at the current and future.*

Keywords— **Heat insulation solar glass (HISG), glass, HISG curtain wall, power generation, heat insulation, energy saving, HISG house, Ordinary house.**

1. INTRODUCTION

In recent years, the energy crisis has prompted many countries on the world more interesting to research renewable energy because of that can be significantly replaced traditional energy sources. Thus, energy saving has been interested and attracted by many scientists as an important and urgent issue due to soaring energy price and gradual depletion of fossil fuels resources. Most of the renewable energy resources currently are available, in which solar energy is one of the most abundant, inexhaustible and clean sources [1], [2]. Therefore, photovoltaics is a truly convenient methods of the electrical energy production on site, directly from the sun, without concern for energy supply or environmental harm, as well as significantly reduced amount of CO_2 gas emission into the natural environment (e.g., greatly reduced greenhouse gas on buildings) in recent years [3], [4].

As we known, the building integrated photovoltaics (BIPVs) are photovoltaic materials, which are able to use to replace conventional building materials in parts of the envelopes or roofs in construction, as a functional part of the building structure or architecturally integrated into the building's design. Moreover, BIPVs can act as shading devices and a semi-transparent material of fenestration. Whereas, other semi-transparent modules can be used in facades or ceilings by using those glass modules to generate various visual effects [5]. Besides, the combination between original solar module and other glass types can be used for many goals (e.g., re-protection, low-e insulation, sun protection or bullet-proof) application in the buildings [6].

Nowadays, the modern buildings are significantly high raised and more energy consuming (or increased power energy need). However, it was required to provide large amount of power energy need and significant decreased emission of CO_2 gas in the environment life, as well as how to design and construct buildings to zero energy, which was not a small challenge for the design of buildings [7], [8]. Thus, related studies have focused on combination methods, system improvements and developments of photovoltaic (PV) cell materials recently. A more clearly comprehensive approach, as

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well as feasibility study, is needed to explore with wider areas how to use existing PV cells to reduce annual energy consumed by high-rise buildings, as well as to conduct and energy saving for feasibility studies in the green building [9]. Thus, to install BIPV modules on buildings suggested the consideration to other problems, first, to avoid energy loss as well as waste during the stand-by mode of the power system or coming from windows, double facades was required to use or a grid-connected system should be used for saving or reducing waste of energy consumption [10]-[12]. Moreover, it was also noted that cooling load could be better than power generated from the PV module system if the system is used as solar shading device [13]-[15], [8], [11]. Therefore, energy consumed by air conditioners or heaters can be significantly reduced, and the building becomes self-sufficient in terms of power demands.

To overcome the challenges about the increasing of power generation from BIPV system used in the green building and to reduce energy consumption of the buildings as well significantly greenhouse gas reducing in buildings. In this study, heat insulation solar glass (HISG) module was applied as curtain walls in the experimental house in Taiwan. The HISG module has been developed successfully by Young et.al. [16], which possessed multiple functions including power generation enhancement, great heat insulation, high energy saving efficiency, good self- cleaning capability and significantly greenhouse gas reduction on buildings.

2. EXPERIMENTAL MATERIALS AND METHODS

2.1 Methods

The structure of PV module (Tandem type) and HISG module were shown in details as Fig. 1. In this work, HISG module was applied as glass curtain wall on the experimental house, which was fabricated and described more details – see the previously report [16].

Herein, we have used normal glass and HISG as curtain walls installed on the Ordinary house and the HISG house, respectively. For comparisons about the illuminative penetration, UV penetration, solar radiation, indoor lighting ability, heat insulation (temperature flow test), energy-saving efficiency (the energy was consumed for the heating and cooling) between the Ordinary house (normal glass) and the HISG house (e.g, midi logger GL 220, T340, etc…), and the power generation measurement of the HISG house was performed by using equipment of SIV-1000M for the investigation.

2.2 Materials

Heater and air conditioner devices were used for testing of saving energy consumption (i.e, SAMPO HX-YB12P: 1250W, and TECO LT63FP1-41003), and other materials such as heat insulation film, air, alcohol, aceton, nano photocatalyst were purchased from Acros. All solutions were prepared using deionized water from a MilliQ system.

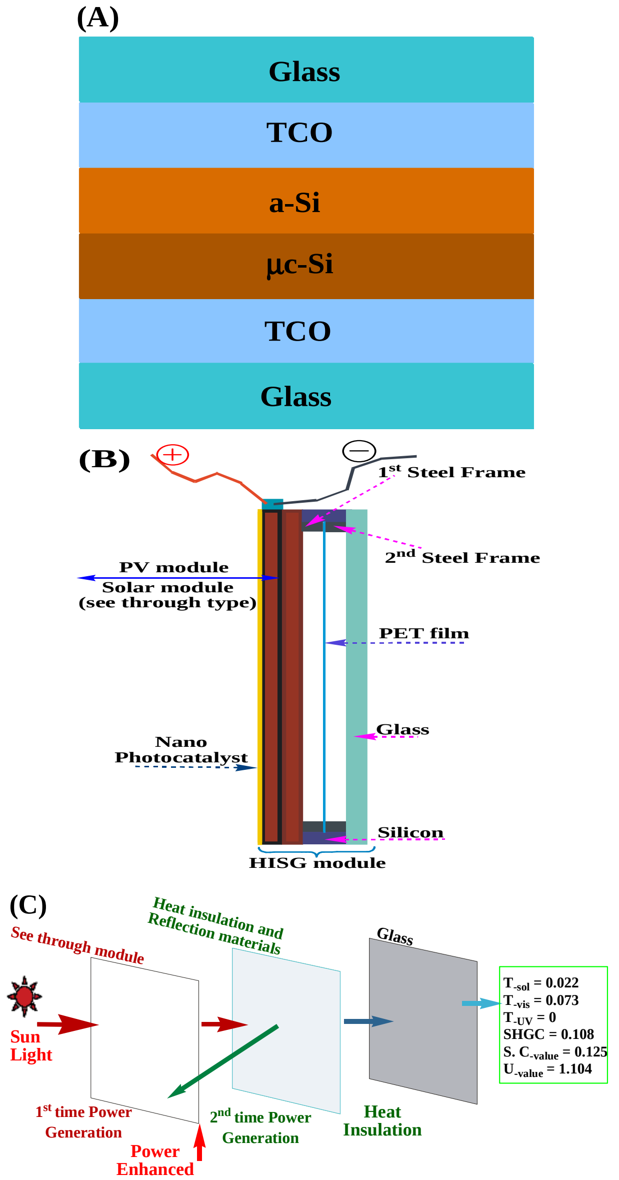


Fig. 1. Structures of (A) original PV module and (B) HISG module (thickness ~28 mm), and (C) Scheme about function theory of HISG (T sol is the solar transmittance, T vis is the visible light transmittance, T UV is the UV transmittance, SHGC is the solar heat gain coefficient, S.C. is the shading coefficient, and U value is the thermal transmittance of HISG) [16].

Table 1. Detail parameters of glazing curtain wall types

Items	Normal glass	HISG
Thickness (mm)	12	28
Visible light	87%	7.15%
U value (W/m^2K)	5.97	1.65
K value (W/mK)	1.05	0.032
Shading coefficient (SC)	0.87	0.144
Houses' size (m)	Length: 3.04; Width: 2.51; Height: 3.17	
Fenestration area (m^2)	Vertical: 24.64; Roof surface: 6.16	
Dimension (mm)	1400×1100	

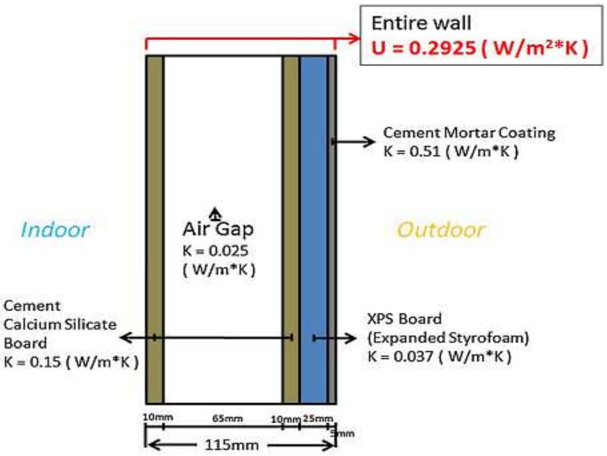


Fig. 2. Thickness and thermal conductivity of all elements of the external envelope of the experimental houses.

3. RESULTS AND DISCUSSION

3.1 Illuminative penetration performance of normal glass and HISG curtain walls on buildings

As shown in Fig. 3, the indoor illumination of the HISG house using HISG curtain wall is 2960 Lux much lower than that of the Ordinary house using normal glass curtain wall to 40087 Lux. In addition, the effective light penetration of normal glass and HISG curtain walls on the houses are estimated about 95% and 32% as compared to outside skylight, respectively. Because, the visible light transmittance of HISG is only 7.15%, whereas the light transmittance of normal glass is being to 87% for contrasting.

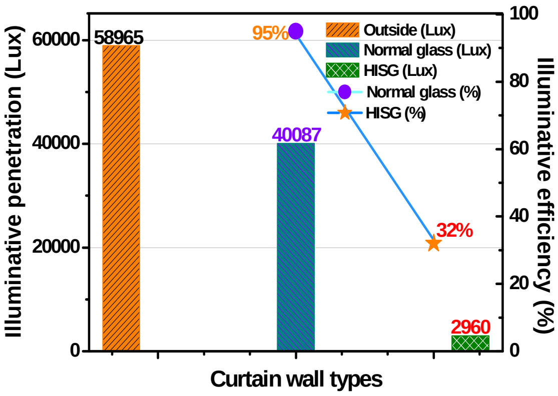


Fig. 3. Intensity and efficiency of illuminative penetration on Normal glass and HISG curtain walls for comparison to the outside skylight.

3.2 Testing of UV penetration on Normal glass and HISG curtain walls

UV penetration performance on the experimental houses was directly inside conducted at the middle point of the houses from 9:00 A.M. to 6:00 P.M. – see Fig. 4. The outdoor ultraviolet value is 5080 (uW/cm^2), and in the Ordinary house using normal glass curtain wall about 1231 (uW/cm^2), while that value in the HISG house using HISG curtain wall dropped to 0 (uW/cm^2). Moreover, the efficiency of UV isolation on normal glass and HISG curtain walls are calculated ~76%, and 100%, respectively. Thus, UV isolation of HISG curtain wall used is much better than that of normal glass curtain wall on the buildings. This isolation achieved because of air layers (with thickness ~12 mm, there are very low UV and thermal transmittance capacities) packaged with PV module to form HISG module. It indicated that the UV isolation on HISG curtain wall is excellent and achieved a 100% UV-blocking rate, completely halting the penetration or transmission of UV light and reducing harm to skin and furniture.

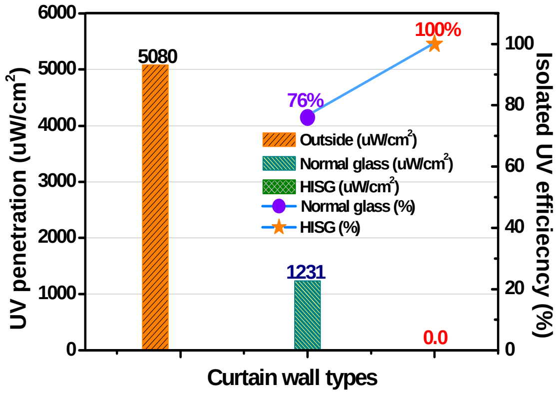


Fig. 4. Intensity and isolated efficiency of UV penetration on Normal glass and HISG curtain walls for comparison to the outside light.

3.3 Testing of solar radiation on Normal glass and HISG curtain walls

The anti-radiant solar efficiency was also performed on normal glass and HISG curtain walls on the experimental houses in this observation. As shown in Fig. 5, the intensity of outdoor solar radiation is measured to 1103 (W/m^2), that intensity on normal glass curtain wall of inside the Ordinary house dropped to 658 (W/m^2), while on HISG curtain wall of inside the HISG house that value is very low only 28.5 (W/m^2). And the effective isolation of solar radiation is also calculated about 40 and 97% for the using of normal glass and HISG curtain walls in the houses, respectively – see Fig. 5.

It demonstrated that radiant heat penetration of HISG curtain wall was significantly lower and its isolated efficiency achieved to 95% as compared to that of normal glass curtain wall and outdoor solar radiation. Thus, we can use HISG as curtain walls, as well as BIPV curtain wall for the replace of normal glass curtain wall on buildings due to the isolated efficiency of radiant heat penetration into the room very high, which can significantly reduce greenhouse gas and inside ambient temperature, and greatly saved energy consumption for heating and cooling of devices inside the houses.

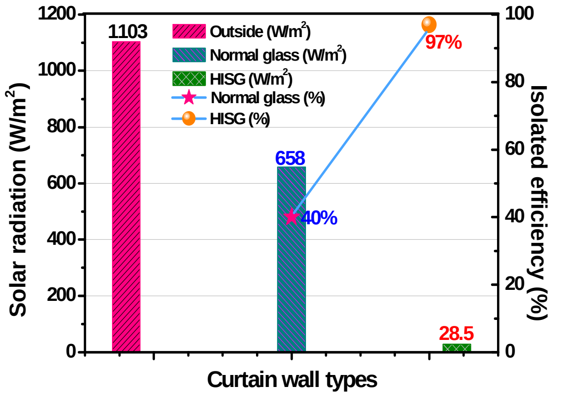


Fig. 5. Intensity and isolated efficiency of solar radiation on Normal glass and HISG curtain walls.

3.4 Indoor lighting measurement of using Normal glass and HISG curtain walls on the experimental houses

Results are shown in Fig. 6, the indoor lighting efficiency of a light 40W at all positions of the HISG house using HISG curtain is much higher than that of the Ordinary house using normal glass curtain for lights 40W used. This efficiency is obtained ~24.9% for the indoor lighting of the HISG house – see Fig. 6. Consequently, the HISG house can be significantly improved and enhanced indoor lighting at night, which is much better than that of the Ordinary house – see Fig. 7. That may be due to the structure of HISG can be conversed and generated power energy from solar energy with high efficiency, which is a sandwich structure containing PV module and a metal reflection film, leading to increased light reflection and significantly enhanced lighting for devices used inside the HISG house. Whereas normal glass curtain of the Ordinary house has no light reflection film layer, the light source cause damage from outside will be easily penetrated into the house and be decreased lighting of devices used inside the house due to the light diffusion to outside environment more, leading to increase energy expense much more.

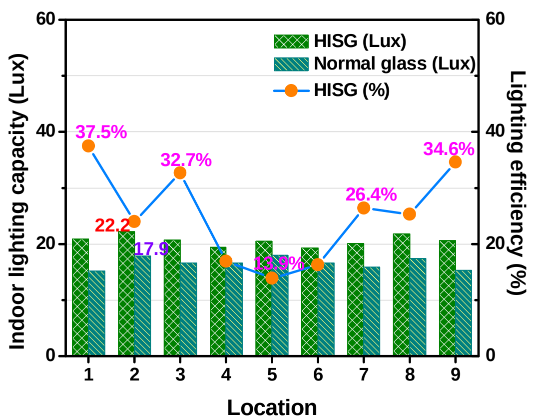


Fig. 6. Intensity and efficiency of indoor lighting of using normal glass and HISG curtain walls on the Ordinary house and the HISG house at various positions, respectively.

Fig. 7. Photograph of inside lighting on (A) the HISG house and (B) the Ordinary house at night, respectively.

3.5 Study of the heat insulation of the experimental houses

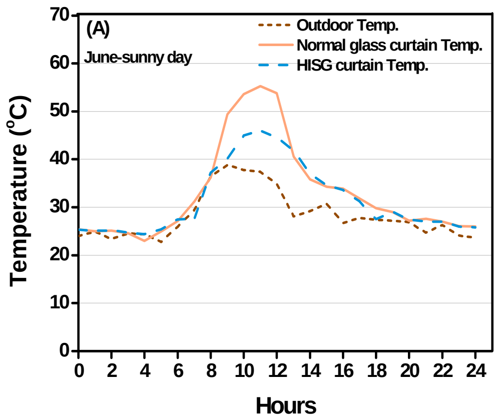
Thermometers were installed in the two houses. The effect of outdoor environment related to the indoor ambient temperature were determined during spring (in March) and summer (in June) seasons from 0:00 A.M. to 12:00 P.M. for comparisons between indoor temperature of the Ordinary house and the HISG house as shown in Fig. 8.

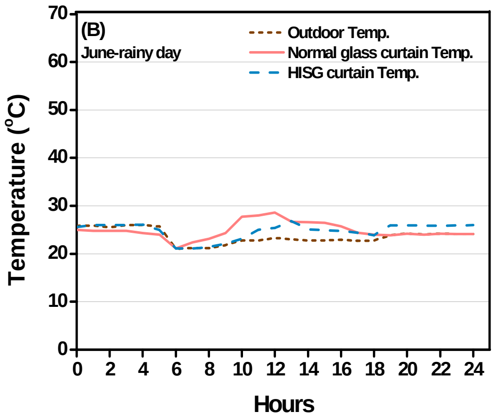
In summer, the outdoor ambient temperature reaches the maximum temperature of 38.8^{o}C at 10:00 A.M., which gradually increases from 36.5^{o}C at 8:00 A.M. to 37.4 and 34.8^{o}C at 11:00-12:00 A.M. and gradually decreases from 1:00-12:00 P.M. in sunny day. As shown in Fig. 8(A), the outdoor temperature rapidly increases from 7:00–12:00 A.M. and gradually decreases from 1:00-12:00 P.M.. Fig. 8(A) also shows a high temperature (~53-54.6^{o}C) in the Ordinary house using normal glass curtain wall from 10:00-12:00 A.M. due to direct exposure to solar radiation, thermal conduction and sealing, leading to interior heat accumulation and increasing temperature inside the house. Whereas, the indoor temperature of the HISG house using HISG curtain wall reaches the maximum value 44.7^{o}C at the same time (11:00 A.M.), which is lower than that of the Ordinary house with difference of 9.9^{o}C. This difference is due to the HISG curtain wall has good heat insulation, low thermal transmission and penetration of solar radiation, achieving to greatly themal insulation and reducing heat accumulation inside the house significantly. The indoor temperatures of the Ordinary house and the HISG house are approximately to the outdoor ambient temperature, when the outdoor temperature gradually decreases and not significantly change from 7:00–12:00 P.M. – see Fig. 8(A).

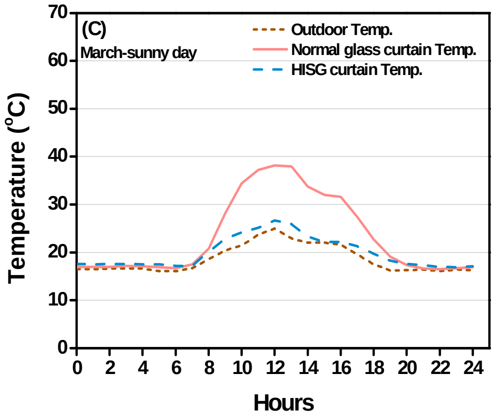
In rainy day, the outdoor temperature plunged from 6:00 A.M. to 6:00 P.M. The indoor temperature of normal glass curtain on the Ordinary house is quite sensitive to the effect of the external environment, which gradually decreases from 12:00 A.M. to 3:00 P.M. – see Fig. 8(B). Since when the rain, the temperature diffusion to outside environment of normal glass curtain was fast due to the good heat transmittance (~60%), quick heat absorption and low heat maintenance of normal glass curtain on the Ordinary house. The HISG curtain is good heat insulation and relatively less affected by outdoor factors. The reaction temperature of HISG curtain is slow, low heat conduction and after the rain around 1:00 P.M. the indoor temperature of HISG curtain in the HISG house is not significantly decrease due to the cooling of HISG curtain is slow with lowly thermal transmittance (~2.6%) and highly thermal maintenance. Thus, the indoor ambient temperature of the HISG house is not changed and still keep at ~26°C, whereas the outdoor and indoor ambient temperature of the Ordinary house ~23°C from 6:00-12:00 P.M. as shown in Fig. 8(B). It indicates that the heat insulation of HISG curtain in the HISG house is much better than that of normal glass curtain in the Ordinary house. Because the indoor temperature of the HISG house is always much lower than that of the Ordinary house from 6:00 A.M. to 6:00 P.M. – see Fig. 8(A, B).

In spring, the maximum indoor temperature of the Ordinary house reached 38.2°C; whereas the outdoor and indoor temperature of the HISG house were respective 25° and 26.7°C at 12:00 A.M. as shown in Fig. 8(C). Results show that the outdoor and indoor temperature of the HISG house is equivalent, which is lower than that of the Ordinary house reached 11.5°C. Sunning duration is 12 h, the incidence angle of the sun rays and solar radiation crossing glazing remains significant on the normal glass curtain, leading to its indoor temperature being much higher than that on the HISG curtain.

During rainy day, the indoor temperature of the Ordinary house and the HISG house is not significant difference (only ~1.2°C at 12:00 A.M.) due to has no sunlight – see Fig. 8(D). Thus, the temperature change between them occurred so small and not significant. The average value of sunlight per hour less than 50 W/m^2 at 0:00–7:00 A.M. and 7:00–12:00 P.M., the outdoor and indoor temperature of the Ordinary house and the HISG house is almost the same as shown in Fig. 8(D). The main reasons may be due to the solar radiation very low, convection and movement between free air molecules low, leading to difficult controlling temperature inside the houses.







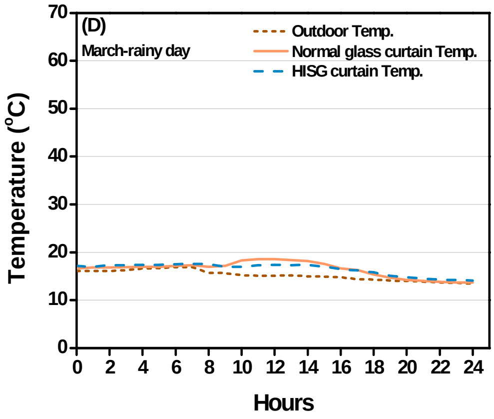


Fig. 8. Hourly variations of indoor and outdoor temperature curves of the HISG house and Ordinary house during summer with (A) sunny day and (B) rainy day; and spring with (C) sunny day and (D) rainy day, respectively.

3.6 The energy-saving investigation of glass curtain wall in the experimental houses

Herein, we have built two 2.51 m (l) × 3.04 m (w) × 3.17 m (h) houses, which were named the HISG House and the Ordinary House (normal glass house) in Taipei of Taiwan for comparison – see Fig. 9.

Fig. 9. Outside appearance of experimental houses: (A) Oridinary House (using Normal glass) and (B) Heat Insulation Solar House (using HISG).

3.6.1 Experiment relating to the energy consumption of air conditioners

Electricity meters (Watt-hour) and air conditioners were installed in two houses to determine the effects of two glass types difference in the energy consumption of air conditioner during the summer as shown in Table 2.

Herein, the air conditioners were set up at 26°C when the outdoor temperature at 35°C, from 6:00 A.M. to 6:00 P.M.. Our experimental results show the air conditioner in the Ordinary House consumed 2.5 kWh of electricity, while in the HISG House consumed only 1.3 kWh. This is estimated about 48% air conditioner energy consumption reduction for HISG compared to the single-layer tempered glass (the Ordinary House). This reduction is very significantly for the using of HISG module in the buildings or Houses due to the extremely small shading coefficient of HISG (nano photocatalyst coated on the HISG module's surface) and high heat radiation anti-reflection from sunlight, as well as reducing large amount of energy consumption because of a good heat insulation layer of HISG, which shown and contributed to excellent heat insulation effects and prevented solar radiation heat from entering the house. Moreover, the U-value of HISG is significantly low, cold air could not easily leave or disperse from the indoor environment, as well as not much lost from electrical energy consumption for the surrounding environment. Thus, the energy-saving efficiency was successful achieved because a large amount of electrical energy consumption from the activation of air-conditioner compressor frequency was significantly reduced.

Table 2. Experimental results about the energy consumption of air conditioner

Item	HISG House	Oridinary House
Time duration	6:00 A.M. – 6:00 P.M.	
Outdoor temperature (°C)	35	
Setting temperature (°C)	26	
Air conditioner consumption (kWh)	1.3	2.5
Energy saving (%)	42.31	–

3.6.2 Experiment for the energy consumption of heaters

Electricity meters (Watt-hour) and heaters were installed in two houses to observe the effects of two glass types in the energy consumption of heaters during the, as shown in Table 3.

In this work, the heaters were set up to 20°C when the outdoor temperature about 14°C, from 6:00 P.M. to 6:00 A.M.. As shown in Table 3, the heater of the Ordinary House consumed 1.5 kWh electrical energy, whereas the HISG House just consumed 0.9 kWh. This result shows a 40% reduction in the energy consumption of heaters for the HISG House as compared to the single-layer tempered glass. This reduction may be due to the HISG has a significantly low U-value, which prevented and decreased expense of hot air from diffusing out of the indoor environment through windows. Therefore, the effective energy-saving was significantly achieved and improved due to the excellent heat retention or good maintain functions of HISG.

Table 3. Experimental results for the heater's energy consumption

Item	HISG House	Oridinary House
Time duration	6:00 P.M. – 6:00 A.M.	
Outdoor temperature (°C)	14	
Setting temperature (°C)	20	
Heater consumption (kWh)	0.9	1.5
Energy saving (%)	40	–

3.7. Power generation performance of the HISG house

The power generation measurement of the HISG house was conducted through practical examinations. HISG modules were installed on all facades of East, South, West, North and Top (Roof) of the HISG house for practical tests were also performed as results shown in Table 4.

HISG modules installed on the roof (Top) were obtained 1.19 kWh of electricity. And HISG modules installed on East, South, West, and North facades as curtain walls of the house were measured to 1.44 kWh of electricity. Thus, the power generation on the HISG house was obtained total 2.63 kWh of electricity per day. For comparison to the Ordinary house, the HISG house can added value of glass power generation due to the HISG integrated renewable solar energy into the building to produce additional power. Consequently, HISG can replace tempered glass (normal glass) in buildings, as new sustainable energy resources, which can significantly reduce greenhouse gas and gradually energy approximately to the zero in the buildings.

Table 4. Results of power generation output on HISG curtain wall by HISG house per day

All facades of the house	East	South	West	North	Top (Roof)	Total power output
Power generating capacity (kWh)	0.45	0.34	0.38	0.27	1.19	2.63
Efficiency (%)	17.1	12.9	14.4	10.3	45.3	100

4. CONCLUSION

HISG curtain wall was successfully applied on the experimental house in Taiwan, which was also widely developed for applying on buildings, as well as the roof of public transport systems. Because HISG was installed for buildings as glass curtain walls, its good self-cleaning capability keeps the module surface clean, leading to reducing the cost required for surface washing. Moreover, HISG has good many functions and properties such as the illuminative penetration quietly high with efficiency of 32%, with 100% UV-blocking rate, low solar radiation 40% as compared to normal glass curtain wall (~97%), greatly enhanced indoor lighting efficiency about 29.4% compared to normal glass curtain wall, highly effective heat insulation due to the indoor temperature of the HISG house was lower than that of the Ordinary house reached 8.9-11^{o}C. In addition, the energy-saving efficiency of the HISG house for heating and cooling were greatly improved to ~40% and 48%, respectively for comparisons to the Ordinary house. Furthermore, HISG curtain wall on the HISG house significantly enhanced and maintained the power generation efficiency and obtained to 2.63 kWh of electricity per day. The resulting increased electrical energy production, highly heat insulation, significantly greenhouse gas reducing, and greatly enhanced energy-saving leads to potential applications in buildings (e.g, Roofing, Skylight – canopies, Curtainwalls – vertical glass, offices, etc…). Consequently, they can be used and applied in the green buildings to significantly greenhouse gas reducing and gradually suitable trend to the zero energy building in future.

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Performance of an Open Ducted Type Very Low Head Cross-Flow Turbine

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Abstract— *Cross Flow Turbine (CFT) known as a Banki turbine or an Ossberger turbine is usually used in the small hydropower, because of its economical and simple structure. This study develops a new kind of CFT suitable for very low head and remote rural region which turbine researched barely before. The new design of the turbine is with open duct inlet channel, without turbine guide vane and nozzle for a more simple structure. The open duct inlet channel can be also suitable in the remote rural region where there are some materials of sediment such as sand and pebble come with flow from upstream that can cause break down. However, the CFT with open duct inlet channel and low head show relatively low efficiency. Therefore, the purpose of this study is developing a new CFT and modifying the turbine inlet open duct bottom line (IODBL) location and angle to improve the performance. The internal flow is investigated to examine the influence of turbine shapes on the performance. The results show that an appropriate turbine IODBL location and angle play an important role on improving the turbine performance, and there is significantly efficiency improvement by optimizing turbine IODBL location.*

Keywords— **Cross flow turbine, very low head, open duct, turbine open angle.**

1. INTRODUCTION

Cross Flow Turbine (CFT) also known as Banki turbine or Ossberger turbine is ideal turbine for the small hydropower, because of its economical and simple structure. This study develops a new kind of CFT with free flow inlet channel and low head, without guide vane and nozzle for a more simple structure. The free flow inlet channel can also be suitable for the remote rural region where there are some sediment such as sand and pebble that come from upstream and enter the turbine structure. However, the CFT with free flow inlet channel and low head show relatively low efficiency. Therefore, the purpose of this study is developing a new CFT and improving the performance of turbine.

In order to increase the efficiency of turbine, some present studies suggest a method of installing an internal deflector into the runner centre which can guide the water flow to a correct angle to improve the performance by CFD analysis and experiment. The authors investigate the influence of different shapes on the performance. The results show that the CFT efficiency could be improved by use of a well-designed internal deflector [1]-[6].

There is also new method to improve performance of the traditional cross flow turbine by supplying air into the chamber to suppress the negative torque where there is hydraulic loss [7], [8]. On the other hand, Choi et. al. [9] performed the experiment and CFD analysis to study the influence of nozzle shape, runner blade angle, and runner blade number on the turbine performance, and also examined the effect of air layer on the performance.

For the very low head CFT, the way of flow entry into the runner is very important. Therefore, the location of IODBL affects the performance of turbine significantly. In this study, a set of turbine IODBL locations are determined to investigate the performance and the internal flow of the very low head CFT.

2. METHODOLOGY

CFT Model

Figure 1 shows the schematic view of the new type very low head CFT model. The structure of the turbine consists of open ducted inlet water channel, runner and draft tube, but guide vane and nozzle, which are a simple structure for turbine. Turbine inlet channel is open duct, which means that there is a free flow in the turbine inlet channel. The draft tube plays a role of reducing the pressure of draft tube to suck the water into turbine chamber. The water flow from turbine inlet channel is separated into two flows: one part of the water flows into the draft tube through the runner passage, which converts the kinetic and pressure energy into the output power of runner, and the other overflows into the downstream with the some materials of sediment, preventing damage to the runner structure.

The turbine height is $H_{turbine}$ = 5m, which also is the draft tube length. The turbine head between the water level of upstream and downstream is H = 4.3m, which is very low in contrast to other typical cases of the hydro turbine.

The number of the blade is $Z = 26$. The diameter of the

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outer runner is D_1=372mm; the inner diameter is D_2= 250mm; D_1/D_2≈0.67. The runner blade inlet angle and outlet angle are β_{b1}=33° and β_{b2}=83°, respectively.

Figure 2 shows the cases and parameters of different turbine IODBL location. To investigate the effect of the turbine IODBL location on the performance, 5 Cases of different turbine IODBL location are conducted. By changing the turbine IODBL location along with changing the turbine open angle, the turbine open angle is changed from 70° to 117°, and the case is named from Cases 1 to 5, respectively. These 5 cases are conducted at the same rotational speed.

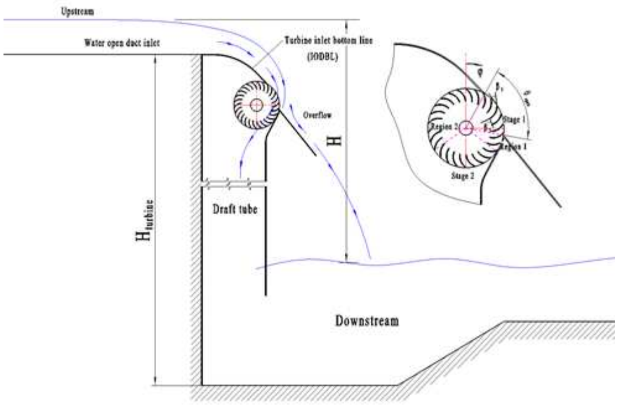

Fig.1. Schematic View of the CFT.

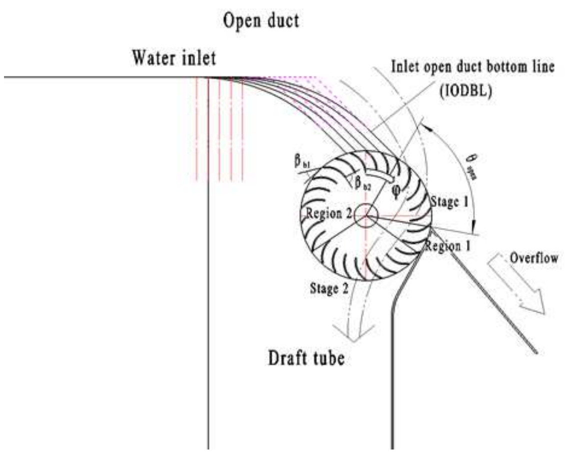

Fig.2. Variation of turbine IODBL location.

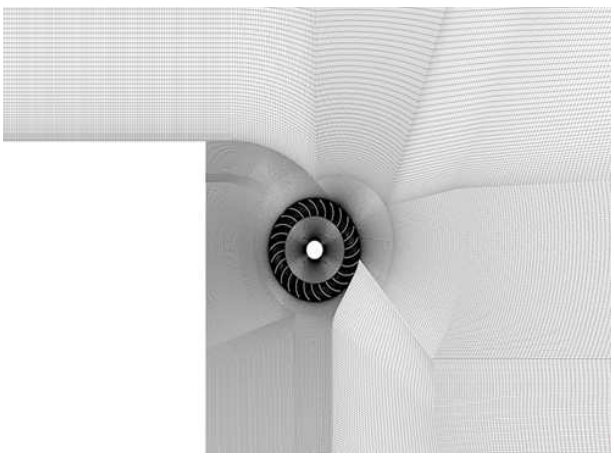

Fig.3. Final Hexahedral Numerical Mesh of Near Area of the Runner.

Numerical Methods

CFD analysis is a useful tool for predicting hydraulic machinery performance at various operating conditions. This study employs a commercial CFD code of ANSYS CFX to conduct CFD analysis. As the direction of gravity is considered, the transient analysis with two phase flow (water and air) is conducted. Two dimensional geometry and mesh are applied in order to decrease the calculation time because the flow in the turbine can be assumed to be uniform of main stream direction which means no flow velocity component in the direction of the thickness.

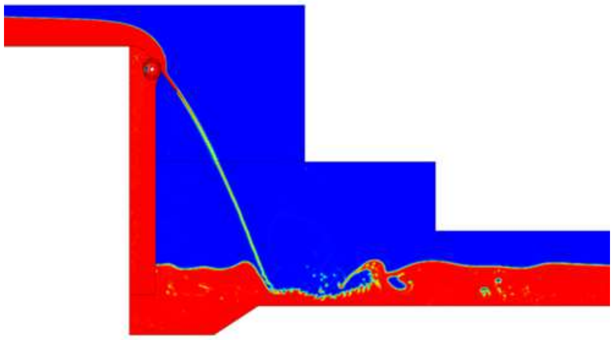

Fig.4. Water volume fraction of CFT by CFD analysis (Case 3)

Table 1. Cases of different turbine IODBL location

Cases	Open angle θ_{open} [°]
Case 1	70
Case 2	88
Case 3	100
Case 4	109
Case 5	117

The boundary condition for normal speed is set for the water flow at the inlet and outlet, and the velocity of 0 m/s is set for the air flow. The boundary condition of opening is set at the top of open duct and downstream domain.

The final hexahedral numerical mesh of near area of the runner and the water volume fraction of CFT are shown in Figure 3 and Figure 4.

Phase change, heat transfer and mass transfer effects are neglected. The circumferential location (θ) direction is clockwise starting from the top of the runner. For convenience, the area of runner passage is divided into four regions: Stages 1 and 2, Regions 1 and 2. Stage 1 obtains first output power and Stage 2 takes the second output power. However, Regions 1 and 2 consume output power by hydraulic loss.

3. RESULTS

Performance Curves of the Investigated Cross Flow Turbine

Figure 4 shows the water volume fraction of CFT in

Case 3 by CFD analysis**.** In this figure, the red part is water, and the blue part is air. Most water from upstream is sucked into the draft tube, and also some water overflows to downstream directly by the effect of gravity.

The draft tube is almost full with water. The upstream and the downstream is free flow and there is a free surface between the air and water. In order to examine the effect of IODBL location on the performance, the performance curves and internal flow are investigated.
The efficiency is determined based on the potential energy difference between upstream and downstream by the following equation:

$$\eta = \frac{T\omega}{\rho g H Q} \qquad (1)$$

where η is the CFT efficiency; T is the output torque; ω is the angular velocity of runner; H is the turbine head and also is the water level difference between upstream and downstream. Q is the water flow rate in through the draft tube.

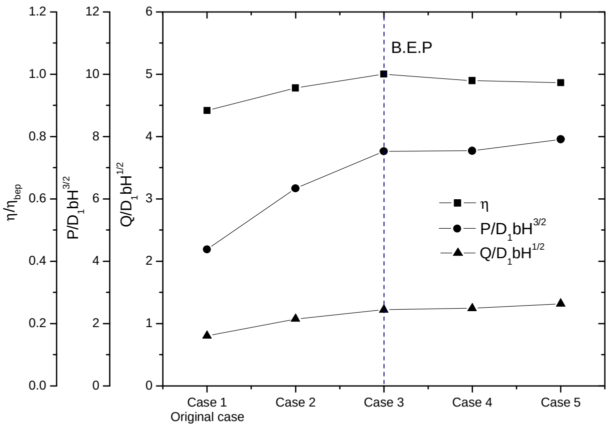

Fig. 5. Performance Curves of the Investigated Cross Flow Turbine.

Figure 5 shows the performance curves by the turbine IODBL location. All the data are normalized as shown in Fig. 5. Case 1 is the original case. From Cases 1 to 5, the output power and flow rate increase along with augmenting the turbine open angle θ_{open}. The present CFD analysis [10] result shows that efficiency drops at small and larger turbine open angle θ_{open}, and turbine has peak efficiency at the Case3. Larger turbine open angle θ_{open} is good for water flowing into the draft tube, and contributes to generating more output power for turbine. A suitable location of turbine IODBL at periphery of runner gives a significant effect on the performance improvement of this turbine. In order to examine the influence factor for the performance variation of the very low head cross flow turbine model, internal flow is investigated.

Velocity Vector and Pressure Contours

The tangential velocity in the blade flow passage is very important because it directly affects the angular momentum of the runner and the output power of the cross flow turbine. In this study, the velocity vector on the runner passage is investigated. Corresponding to the IODBL angle, Cases 1, 3 and 5 are chosen as typical cases to investigate the internal flow influenced by IODBL location on the periphery of runner. Figure 6 shows velocity vectors at Stage 1 and 2, and the pressure contours at runner passage by the three typical cases. From the figure of the velocity vectors, it can be observed that there is uniform flow at the Stage 1 of runner passage in Case 1, but there are large recirculating flow at Stage 1 in Case 3. Larger turbine open angle θ_{open} causes the hydraulic loss at Stage 1 by recirculating flow that occurs to a large extent. However, at Stage 2 of runner passage, the velocity vectors show uniform outflow in Case3, but the flow in the runner passage separate with the blade in Case 1, and the change in fluid flow quite drastically between the three cases. It is conjectured that this change at Stages 1 and 2 discussed aforementioned affects the turbine performance as seen by the performance curve.

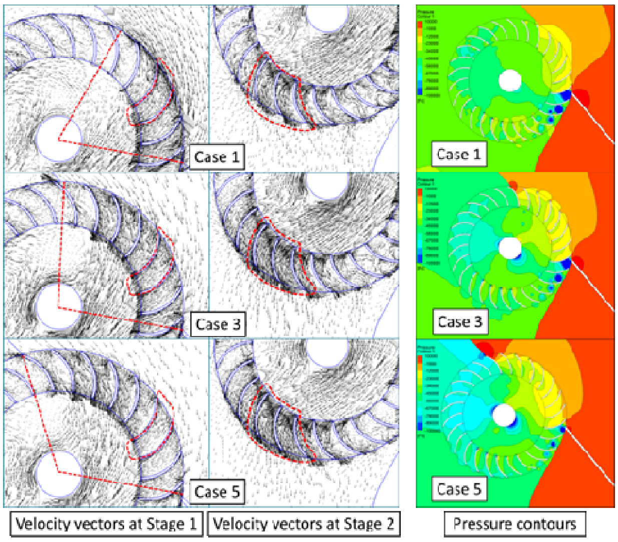

Fig. 6. Velocity Vectors at Stages 1 and 2, and Pressure Contours at Runner Passage.

From the pressure contours at runner passage shown in Figure 6, there exists a high pressure region on the pressure side of runner blades at the leading position of the flow direction. The high pressure on the blade pressure side means the power to the rotation of the runner. The more pressure difference between the blade pressure and suction side, the more output power is generated. The pressure distribution is relatively even at blade pressure and suction side at Stage 1 in Case 5, but there exits obviously pressure difference at blade pressure and suction side in Case 1. However, there is contrary trend of the pressure distribution at Stage 2. The effect of increasing the turbine open angle gives obviously rising pressure difference at Stage 2, but the effect at the Stage 1 is opposite.

Velocity Triangle and Pressure Contours

For turbo-machines, the water flow velocity triangle on the entrance and exit blade passage is a very important factor that affects the performance of the cross flow turbine. In order to investigate the effect of turbine IODBL on the internal flow and performance in detail, the velocity triangle on the runner periphery is measured. Figure 7 presents the flow velocity triangle at the entrance of Stage 1 and the exit of Stage 2, and the velocity triangle on a blade of the cross flow turbine. α is the absolute angle that is between absolute velocity (V) and the runner tip velocity (u). β is the relative angle that is between relative velocity (w) and the runner tip velocity (u). β_{b1} is the inlet angle of blade. The power delivered from the fluid is thus [11]-[13] This is the Euler turbo-machine equation, showing that power is functions of runner tip velocities ($u_{1,2}$) and the absolute water flow tangential velocities ($V_{u1,2}$). This equation is assumed by neglecting the energy loss at runner center passage between exit of Stage 1 and entrance of Stage 2.

$$p_w = \rho Q(u_1 V_{u1} - u_2 V_{u2}) \qquad (2)$$

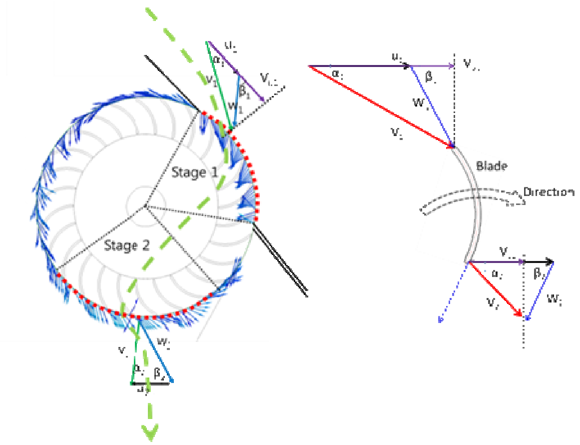

Fig.7. Diagram View of Velocity Triangle.

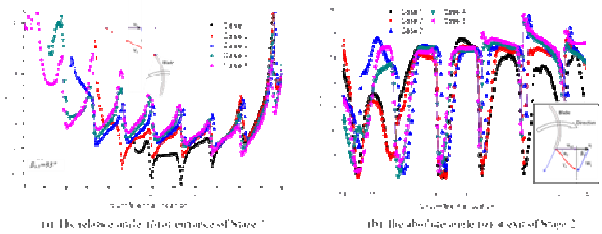

Fig. 8. Velocity Triangle Distribution Curves.

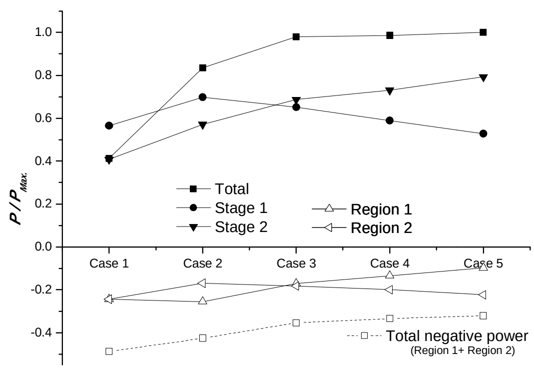

Fig. 9. Averaged Output Power Distribution Curve on the Circumferential.

In Equation (2) it can be seen that for maximum output power, the absolute water flow tangential velocity at outlet of Stage 2 should V_{u2}=0, in which case the absolute angle α = 90º.Moreover, for the water flow into the runner passage, the relative angle *β* should be close to the blade inlet angle β_{b1}. Figure 8 reveals the velocity triangle distribution curves at the entrance of Stage 1 and the exit of Stage 2, respectively. From the relative angle (*β*) distribution at entrance of Stage 1, it can be seen that the *β* of Case 1 is the closest to β_{b1}, there is no separation flow between water flow and the blade surface in the runner passage, this phenomenon is also proved in Figure 7. From Cases 2 to 5, the relative angle *β* is farther away from blade inlet angle β_{b1}, which means that larger turbine open angle causes relative angle farther away the best flow inlet angle. From the absolute angle at exit of Stage 2, the absolute angle of flow has almost no change from the circumferential location of 180º-220º, which has most of the output power generated. The effect of the turbine IODBL location is poor on the absolute angle at flow exit of Stage 2.

Output Power Distribution

The runner passage area is divided by four regions to check the output power distribution on the circumferential. Figure 9 shows the averaged output power distribution on the circumferential by the four regions (Stages 1, 2 and Regions 1, 2). The total negative power is the sum of the output powers at Regions 1 and 2, which are hydraulic loss by recirculating flow. The total negative power keeps stable after Case 3, and that reduces rapidly from Cases 1 to 3. By opening the open angle, the hydraulic energy loss at Regions 1 and 2 is suppressed effectively, but that impact becomes small if the turbine with too large open angle. Therefore, even though the relative angle of Case 1 is the closest to β_{b1}, here exists large extent of loss output at Regions 1 and 2. Thus, the efficiency of Case 1 shows lower than that of Case 3. Moreover, the output power rises at Stage 2 for larger open angle, but it reduces at Stage 1 except for Case 1. The output power at Stage 1 in Case 1 is small, so it is conjectured that the circumferential range of Case 1 at Stage 1 is the smallest one that contributes the least output power.

4. CONCLUSIONS

This paper presents the characteristic of a very low head cross flow turbine with open ducted inlet channel, the performance and internal flow improvement by optimizing the IODBL location. The performance of the turbine is improved significantly by a suitable location of turbine IODBL at the periphery of the runner.

The larger turbine open angle gives larger pressure difference at Stage 1 and reduces the recirculating flow at Stage 2. However, there is a large recirculating flow at Stage 1 when the turbine open angle and the water flow increase separately with the blade surface, which exists hydraulic energy loss.

The effect of the increase of the turbine open angle on the relative angle at flow entrance of Stage 1 is farther way from the blade inlet angle, but there exists a large extent of loss output at Regions 1 and 2 with larger turbine open angle. Thus, the efficiency of Case 1 shows lower than that of Case 3.

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Optimal Reactive Power Dispatch Using Artificial Bee Colony Method

Vo Ngoc Dieu, Nguyen Huu Thien An*, and Vo Trung Kien

Abstract— *This paper proposes an artificial bee colony (ABC) algorithm for solving optimal reactive power dispatch (ORPD) problem. The proposed ABC can deal with different objectives of the problem such as minimizing the real power losses, improving the voltage profile, and enhancing the voltage stability and properly handle various constraints for reactive power limits of generators and switchable capacitor banks, bus voltage limits, tap changer limits for transformers, and transmission line limits. The proposed method has been tested on the IEEE 30-bus and IEEE 118- bus systems and the obtained results are compared to those from Particle Swarm Optimizer (PSO), Self-Organizing Hierarchical Particle Swarm Optimizer - Time Varying Acceleration Coefficients (HPSO-TVAC), Particle Swarm Optimization - Time Varying Acceleration Coefficients (PSO-TVAC), and other methods in the literature. The result comparison has shown that the proposed method can obtain total power loss, voltage deviation or voltage stability index less than the others for the considered cases. Therefore, the proposed ABC can be a favorable method for implementation in the optimal reactive power optimization problems.*

Keywords— **Constriction factor, optimal reactive power dispatch, artificial bee colony method, voltage deviation, voltage stability index.**

1. INTRODUCTION

Optimal reactive power dispatch (ORPD) is to determine the control variables such as generator voltage magnitudes, switchable VAR compensators, and transformer tap setting so that the objective function of the problem is minimized while satisfying the unit and system constraints [1]. In the ORPD problem, the objective can be total power loss, voltage deviation at load buses for voltage profile improvement [2], or voltage stability index for voltage stability enhancement [3]. ORPD is a complex and large-scale optimization pro[1]blem with nonlinear objective and constraints. In power system operation, the major role of ORPD is to maintain the load bus voltages within their limits for providing high quality of services to consumers.

The problem has been solved by various techniques ranging from conventional methods to artificial intelligence based methods. Several conventional methods have been applied for solving the problem such as linear programming (LP) [4], mixed integer programming (MIP) [5], interior point method (IPM) [6], dynamic programming (DP) [7], and quadratic programming (QP) [8]. These methods are based on successive linearizations and use gradient as search directions. The conventional optimization methods can properly deal with the optimization problems of deterministic quadratic objective function and differential constraints. However, they can be trapped in local minima of the ORPD problem with multiple minima [9]. Recently, meta-heuristic search methods have become popular for solving the ORPD problem due to their advantages of simple implementation and ability to find near optimum solution for complex optimization problems. Various meta-heuristic methods have been applied for solving the Problem such as evolutionary programming (EP) [9], genetic algorithm (GA) [3], ant colony optimization algorithm (ACOA) [10], differential evolution (DE) [11], harmony search (HS) [12], etc. These methods can improve optimal solutions for the ORPD problem compared to the conventional methods but with relatively slow performance.

Artificial bee colony (ABC) algorithm is a search method, which is inspired by the foraging behavior of honeybee swarm, and target discrete optimization problems. The ABC algorithm that was developed by Karaboga [13] is a population-based heuristic algorithm. In this algorithm, bees are members of a family which live in organized honeybee swarm. The bees consist of two groups. ABC algorithm has been applied to various optimization problems such as compute-industrial engineering, hydraulic engineering, aviation and space science and electronic engineering since 2005 [14-16]. ABC algorithm was firstly applied to ORPD problem by Ozturk and is tested on IEEE 10 bus-test system [17].

In this paper, the proposed method has been tested on the IEEE 30-bus and IEEE 118-bus systems and the obtained results are compared to those from particle swarm optimizer (PSO), self-organizing hierarchical particle swarm optimizer - time varying acceleration coefficients (HPSO-TVAC), particle swarm optimization - time varying acceleration coefficients (PSO-TVAC), and other methods in the literature. The result comparison has shown that the proposed method can obtain total power loss, voltage deviation or voltage stability index less than the others for the considered cases. Therefore, the proposed ABC can be a favorable method for implementation in the optimal reactive power

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optimization problems.

2. PROBLEM FORMULATION

The objective of the ORPD problem is to minimize is to optimize the objective functions while satisfying several equality and inequality constraints.

Mathematically, the problem is formulated as follows:

$$MinF(x,u) \tag{1}$$

where the objective function *F(x,u)*can be expressed in one of the forms as follows:

- Real power loss:

$$F(x,u) = P_{loss} = \sum_{i=1}^{N_l} g_l \begin{bmatrix} V_i^2 + V_j^2 \\ -2V_iV_j\cos(\delta_i - \delta_j) \end{bmatrix} \tag{2}$$

- Voltage deviation at load buses for voltage profile improvement [2]:

$$F(x,u) = VD = \sum_{i=1}^{N_d} \left| V_i - V_i^{sp} \right| \tag{3}$$

where V_i^{sp} is the pre-specified reference value at load bus *i*, which is usually set to 1.0 pu.

- Voltage stability index for voltage stability enhancement [3], [18]:

$$F(x,u) = L_{\max} = \max\{L_i\}; i = 1,..., N_d \tag{4}$$

where L_i is voltage stability index at load bus *i*

For all the considered objective functions, the vector of dependent variables *x* represented by:

$$x = [Q_{gl},...,Q_{gN_g}, V_{l1},...,V_{lN_d}, S_1,...,S_{N_l}]^T \tag{5}$$

and the vector of control variables *u* represented by:

$$u = [V_{gl},...,V_{gN_g}, T_1,...,T_{N_t}, Q_{c1},...,Q_{cN_c}]^T \tag{6}$$

The problem includes the equality and inequality constraints as follows:

a) Real and reactive power flow balance equations at each bus:

$$P_{gi} - P_{di} = V_i \sum_{j=1}^{N_b} V_j \left[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j) \right] \tag{7}$$

$$i = 1,..., N_b$$

$$Q_{gi} - Q_{di} = V_i \sum_{j=1}^{N_b} V_j \left[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j) \right] \tag{8}$$

$$i = 1,..., N_b$$

b) Voltage and reactive power limits at generation buses:

$$V_{gi,\min} \le V_{gi} \le V_{gi,\max}; i = 1,..., N_g \tag{9}$$

$$Q_{gi,\min} \le Q_{gi} \le Q_{gi,\max}; i = 1,..., N_g \tag{10}$$

c) Capacity limits for switchable shunt capacitor banks:

$$Q_{ci,\min} \le Q_{ci} \le Q_{ci,\max}; i = 1,..., N_c \tag{11}$$

d) Transformer tap settings constraint:

$$T_{k,\min} \le T_k \le T_{k,\max}; k = 1,..., N_t \tag{12}$$

e) Security constraints for voltages at load buses and transmission lines:

$$V_{li,\min} \le V_{li} \le V_{li,\max}; i = 1,..., N_d \tag{13}$$

$$S_l \le S_{l,\max}; l = 1,..., N_l \tag{14}$$

where the S_l is the maximum power flow between bus *i* and bus *j* determined as follows:

$$S_l = \max\left\{ \left| S_{ij} \right|, \left| S_{ji} \right| \right\} \tag{15}$$

3. ARTIFICIAL BEE COLONY ALGORITHM

3.1 Artificial bee colony (ABC) algorithm:

ABC algorithm was proposed by Karaboga in 2005 [15] and the flow chart of this algorithm is shown in Fig. 1. ABC algorithm is a population-based algorithm to be developed by taking into con-sideration the thought that how honeybee swarm finds food. The honeybee swarm in this algorithm is divided into two groups: worker bees and non-worker bees including onlooker bees and explorer bees. The onlooker bees are produced with certain intervals around the worker bees. If the produced onlooker bees find a source having higher fitness value, these bees are replaced by worker bees; otherwise the base value is increased by 1. If the base value exceeds its certain limit, this source is abandoned and the bee of the source is reproduced with the explorer bee. The bees having the best fitness value among all the reproduced bees are repre-sented in the next iteration. The following steps are implemented until the stopping criterion in ABC algorithm has been achieved.

3.1.1. Initial population:

The initial population is very important in heuristic methods and can be produced by different ways. One of them is the random producing and is used in this study. The initial population of the algorithm is produced within its limits according to the equation below:

$$u_{ij} = u_{\min i,j} + rand \times (u_{\max,j} - u_{\min,j}) \tag{16}$$

where $u_{min,j}$ and $u_{max,j}$ represent the minimum and maximum of the variable j. The value of *rand* is between 0 and 1.

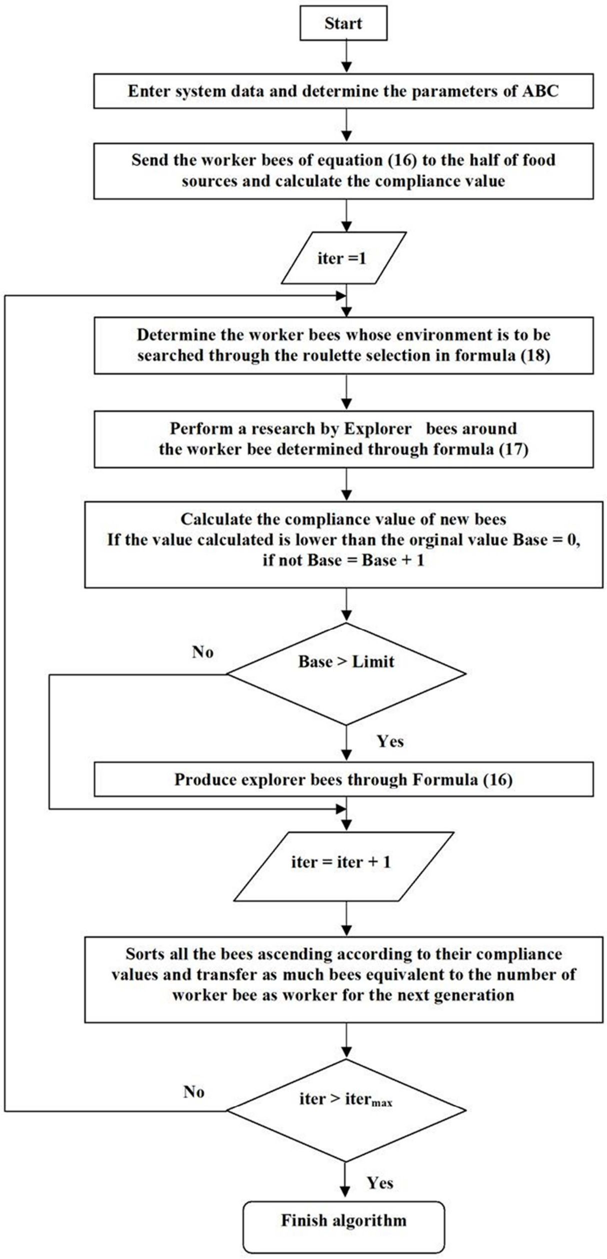

Fig.1. Flow chart of the ABC algorithm.

3.1.2. Worker bees

The worker bees are produced according to Eq. (17) and by using knowledge of the bees in the population. The feature of worker bees is that they are produced by taking the advantage from the sources which is previously discovered.

$$v_{ij} = \min(u_{ij}, u_{kj}) + \max(u_{ij}, u_{kj}) \times (rand - 0.5) \times 2] \quad (17)$$

where v_{ij} represents the produced worker bee, $\min(u_{ij}, u_{kj})$ and $\max(u_{ij}, u_{kj})$ represent the lower and upper limit of the variables u_{ij} and u_{kj}, respectively.

3.1.3. Onlooker bees:

The onlooker bees are produced by local searching with certain intervals around the bees determined by roulette selection method among worker bees. If the source found by the produced onlooker bees is better than one found by worker bees, the onlooker bee is assigned as worker bee. Then the base value is increased by 1. The efficiency of a bee in the population is determined with Eq. (18) . In the roulette method, the probability of a bee having high efficiency to be selected is high.

$$P_i = \frac{fit_i}{\sum_{n=1}^{SN} fit_n} \quad (18)$$

where *SN* is the number of the food sources which is equal to the number of employed bees, fit_i is the modified fitness value of *i*th solution which is proportional to the nectar amount of the food source in the position *i* and is given as follows:

$$fit_i = \frac{1}{f_i} \quad (19)$$

where f_i is the fitness value that is obtained separately for each individual through Eq. (20) .

3.1.4. Explorer bees

Worker bees whose the sources have been come an end become explorer bees and start to search new food source nectar randomly, for example by Eq. (16). There is not any guidance of the explorer bee for searching new food sources. They primarily try to find any kind of food source. The worker bee whose food source nectar has been come an end or the profitability of the food source drops under a certain level is selected and classified as the explorer bee.

3.1.5 ABC for the ORPD problem

For implementation of the proposed ABC to the problem, each particle position representing for control variables is defined as follows:

$$x_d = [V_{g1d},\dots,V_{gN_g d}, T_{1d},\dots,T_{N_t d}, Q_{c1d},\dots,Q_{cN_c d}]^T \quad (20)$$
$$d = 1,\dots,NP$$

The fitness function to be minimized is based on the problem objective function and dependent variables including reactive power generations, load bus voltages, and power flow in transmission lines. The fitness function is defined as follows:

$$F_T = F(x,u) + K_q \sum_{i=1}^{N_g} (Q_{gi} - Q_{gi}^{\lim})^2 + K_v \sum_{i=1}^{Nd} (V_{li} - V_{li}^{\lim})^2 + K_s \sum_{l=1}^{N_l} (S_l - S_{l\max})^2 \quad (21)$$

where K_q, K_v and K_s are penalty factor for reactive power generations, load bus voltages, and power flow in transmission lines, respectively.

The limits of the dependent variables in (21) are determined based on their calculated values as follows:

$$x^{\lim} = \begin{cases} x_{\max} & x > x_{\max} \\ x_{\min} & x < x_{\min} \end{cases} \quad (22)$$

where x and x^{lim} respectively represent for the calculated value and limits of Q_{gi}, V_{li}, S_{lmax}.

The overall procedure of the proposed ABC for solving the ORPD problem is addressed as follows:

Step 1: Choose the controlling parameters for ABC including number of particle *NP*, maximum number of iterations $iter_{max}$, and penalty factors for constraints.

Step 2: The ith individual position in ABC method is initialized as follows (16).

Step 3: Set the iterators: *iter* = 1

Step 4: For each particle, calculate value of dependent variables based on power flow solution using Matpower toolbox 4.1.
Calculate the fitness function as follows (21).
Set the current value of the X_{id} is the best value.
Set the best value of the *i*th individual as follows (18)
In which X_{id} is the best position of individual *i* in the group of individuals in the population.

Step 5: Locate X_d employed bees as follows (17).

Step 6: Solve power flow using Matpower toolbox based on the newly obtained value of position for each particle.
Recalculate Fitness function for Employed bees.
Compare the value of this position Fitness with Fitness initialization values.
If the value calculated is lower than the orginal value *Base*= 0, if not *Base* = *Base* + 1.

Step 7: If *Base* >*Limit*, go to ther next step. Otherwise, go to step 9.

Step 8: Produce explorer bees through Formula (16)

Step 9: *iter* = *iter* +1.

Step 10: Sorts all the bees ascending according to their compliance values and transfer as much bees equivalent to the number of worker bee as worker for the next generation.

Step 11: If *iter* < $iter_{max}$ return to Step 4. Otherwise, stop.

4. NUMERICAL RESULTS

The proposed ABC has been tested on the IEEE 30-bus and 118-bus systems with different objectives including power loss, voltage deviation, and voltage stability index. The data for these systems can be found in [19], [20]. The characteristics and the data for the base case of the test systems are given in Tables 1 and 2, respectively.

The algorithms of the ABC methods are coded in Matlab R2009b and run on an Intel Core 2 Duo CPU 2.00 GHz with 2 GB of RAM PC. The parameters of the ABC methods for the test systems are summarized in Table 3. Number of individuals in a population for each test system is decided based on trial simulation run.

4.1 IEEE 30-bus system

In the test system, the generators are located at buses 1, 2, 5, 8, 11, and 13 and the available transformers are located on lines 6-9, 6-10, 4-12, and 27-28. The switchable capacitor banks will be installed at buses 10, 12, 15, 17, 20, 21, 23, 24, and 29 with the minimum and maximum values of 0 and 5 MVAR, respectively. The limits for control variables are given in [11], generation reactive power in [21], and power flow in transmission lines in [22].

The results obtained by the ABC methods for the system with different objectives including power loss, voltage deviation for voltage profile improvement, and voltage stability index for voltage enhancement are given in Tables 4, 5, and 6, respectively and the solutions for best results are given in Tables A1, A2, and A3 of Appendix.

The obtained best results from the proposed ABC method are compared to Gravitational Search Algorithm (GSA), comprehensive learning particle swarm optimization (CLPSO) [23], Self-Organizing Hierarchical Particle Swarm Optimizer - Time Varying Acceleration Coefficients (HPSO-TVAC), Particle Swarm Optimization - Time Varying Acceleration Coefficients (PSO-TVAC) [24] for different objectives as given in Table 7.

It can be seen from the data in Table 7 that the results obtained from the ABC method are less than another methods with total power loss, voltage deviation, and voltage stability index. As shown in Table 4,5,6, the computational time of ABC method is highest but the difference is not much. Best results are given in Tables A1, A2, and A3 of Appendix with all the constraint of voltage, reactive power at the generator node and the transformer index are satisfied.

4.2 IEEE 118-bus system

In this system, the position and lower and upper limits for switchable capacitor banks, and lower and upper limits of control variables are given in [23].

Table 1. Characteristics of test systems

System	No. of branches	No. of Generation buses	No. of transformers	No. of capacitor banks	No. of control variables
IEEE 30 bus	41	6	4	9	19
IEEE 118 bus	186	54	9	14	77

Table 2. Base case for test systems

System	$\sum P_{di}$	$\sum Q_{di}$	$\sum P_{gi}$	$\sum Q_{gi}$
IEEE 30 bus	283.4	126.2	287.92	89.2
IEEE 118 bus	4242	1438	4374.86	795.68

Table 3: Parameters for ABC algorithm

Worker bees	Onlooker bees	Explorer bees	Limit	Run ABC many times
10	10	10	20	100

Table 4. Results by ABC methods for the IEEE 30-bus system with power loss objective

Method / Function	PSO-TVAC[22]	HPSO-TVAC[22]	ABC
Min P_{loss} (MW)	4.5356	4.5283	4.5194
Avg. P_{loss} (MW)	4.5912	4.5581	4.8892
Max P_{loss} (MW)	4.9439	4.6112	5.3815
Std.dev. P_{loss} (MW)	0.0592	0.0188	0.1885
VD	1.9854	1.9315	2.0317
L_{max}	0.1257	0.1269	0.1263
Avg. CPU time (s)	10.85	10.38	14.477

Table 5. Results by ABC methods for the IEEE 30-bus system with voltage deviation objective

Method / Function	PSO-TVAC[22]	HPSO-TVAC[22]	ABC
Min VD	0.1210	0.1136	0.0992
Avg. VD	0.1529	0.1340	0.1870
Max VD	0.1871	0.1615	0.4394
Std.dev. VD	0.0153	0.0103	0.0718
P_{loss} (MW)	5.3829	5.7269	5.4582
L_{max}	0.1485	0.1484	0.1494
Avg. CPU time (s)	9.88	9.59	11.747

Table 6. Results by ABC methods for the IEEE 30-bus system with voltage stability index objective

Method / Function	PSO-TVAC[22]	HPSO-TVAC[22]	ABC
Min L_{max}	0.1248	0.1261	0.1247
Avg. L_{max}	0.1262	0.1275	0.1296
Max L_{max}	0.1293	0.1287	0.1545
Std.dev. L_{max}	0.0009	0.0006	0.0049
P_{loss} (MW)	4.8599	5.2558	4.7359
VD	1.9174	1.6830	2.1461
Avg. CPU time (s)	13.39	13.05	15.760

Table 7. Comparison of best results for the IEEE 30-bus system

Method / Function	Power loss (MW)	Voltage deviation (VD)	Stability index (L_{imax})
GSA[27]	4.6166	0.1064	-
CLPSO[28]	4.5615	-	-
PSO-TVAC[22]	4.5356	0.1210	0.1248
HPSO-TVAC[22]	4.5283	0.1136	0.1261
ABC	4.5194	0.0992	0.1247

Table 8. Results by ABC methods for the IEEE 118-bus system with power loss objective

Method / Function	PSO-TVAC[22]	PSO[28]	CLPSO[28]	ABC
Min P_{loss} (MW)	124.3335	131.99	130.96	122.6792
Avg. P_{loss} (MW)	129.7494	132.37	131.15	138.7797
Max P_{loss} (MW)	134.1254	134.5	132.74	160.8688
Std.dev. P_{loss} (MW)	2.1560	0.00032	0.000085	5.4653
VD	1.4332	3.0027	1.8525	2.8697
L_{max}	0.0679	0.2049	0.1461	0.0629
Avg. CPU time (s)	85.32	1215	1472	98.203

Table 9. Results by ABC methods for the IEEE 118-bus system with voltage deviation objective

Method / Function	PSO-TVAC[22]	PSO[28]	CLPSO[28]	ABC
Min VD	0.3921	2.2359	1.6177	0.3212
Avg. VD	0.4724	-	-	0.4315
Max VD	0.5407	-	-	0.5231
Std.dev. VD	0.0316	-	-	0.0488
P_{loss} (MW)	179.7952	132.16	132.06	176.5858
L_{max}	0.0667	0.1854	0.1210	0.0680
Avg. CPU time (s)	78.70	-	-	84.464

Table 10. Results by ABC methods for the IEEE 118-bus system with stability index objective

Method / Function	PSO-TVAC[22]	PSO[28]	CLPSO[28]	ABC
Min L_{max}	0.0607	0.1388	0.0965	0.0599
Avg. L_{max}	0.0609	-	-	0.0662
Max L_{max}	0.0613	-	-	0.0733
Std.dev. L_{max}	0.0001	-	-	0.0029
P_{loss} (MW)	184.5627	133.08	132.08	217.0914
VD	1.2103	2.3262	2.8863	2.0428
Avg. CPU time (s)	119.22	-	-	128.582

Table 11. Comparison of best results for the IEEE 118-bus system

Method / Function	Power loss (MW)	Voltage deviation (VD)	Stability index (L_{imax})
PSO-TVAC[22]	124.3335	0.3921	0.0607
PSO[28]	131.99	2.2359	0.1388
CLPSO[28]	130.96	1.6177	0.0965
ABC	122.6792	0.3212	0.0599

The obtained results by the ABC methods for the system with different objectives similar to the case of IEEE 30 bus system are given in Tables 8, 9, and 10, respectively and the comparison of best results from methods for different objectives is given in Table 11. It can be seen from the data in Table 11 that the results obtained from the ABC method are less than others methods with total power loss, voltage deviation, and voltage stability index. As shown in Table 8, 9, the computational time of ABC method is slower than others methods but in Table 10, the computational time of ABC method is very fast. So that, the computational time of ABC method is fast but in a few cases, it is slow.

5. CONCLUSION

In this paper, the ABC method has been effectively and efficiently implemented for solving the ORPD problem. The proposed ABC has been tested on the IEEE 30-bus and IEEE 118-bus systems with different objectives including power loss, voltage deviation, and voltage stability index. The test results have shown that proposed method can obtain total power loss, voltage deviation, or voltage stability index less than other methods for test cases. Therefore, the proposed ABC could be a useful and powerful method for solving the ORPD problem.

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APPENDIX

The best solutions by ABC methods for the IEEE 30- bus system with different objectives are given in Tables A1, A2, and A3.

Table A1. Best solutions by PSO methods for the IEEE 30-bus system with power loss objective

Variables	PSO-TVAC	HPSO-TVAC	ABC
V_{g1}	1.1000	1.1000	1.1000
V_{g2}	1.0957	1.0941	1.0948
V_{g5}	1.0775	1.0745	1.0714
V_{g8}	1.0792	1.0762	1.0759
V_{g11}	1.1000	1.0996	1.1000
V_{g13}	1.0970	1.1000	1.1000
T_{6-9}	1.0199	1.0020	1.0262
T_{6-10}	0.9401	0.9498	0.9164
T_{4-12}	0.9764	0.9830	0.9782
T_{27-28}	0.9643	0.9707	0.9718
Q_{c10}	4.5982	2.3238	5.0000
Q_{c12}	2.8184	2.8418	5.0000
Q_{c15}	2.3724	3.6965	3.9341
Q_{c17}	3.6676	4.9993	5.0000
Q_{c20}	4.3809	3.1123	4.2164
Q_{c21}	4.9146	4.9985	5.0000
Q_{c23}	3.6527	3.5215	3.2097
Q_{c24}	5.0000	4.9987	4.9997
Q_{c29}	2.1226	2.3743	2.5913

Table A2. Best solutions by PSO methods for the IEEE 30-bus system with voltage deviation objective

Variables	PSO-TVAC	HPSO-TVAC	ABC
V_{g1}	1.0282	1.0117	1.0232
V_{g2}	1.0256	1.0083	1.0219
V_{g5}	1.0077	1.0169	1.0142
V_{g8}	1.0014	1.0071	1.0034
V_{g11}	1.0021	1.0707	1.0460
V_{g13}	1.0046	1.0060	0.9914
T_{6-9}	1.0125	1.0564	1.0508
T_{6-10}	0.9118	0.9076	0.9000
T_{4-12}	0.9617	0.9545	0.9545
T_{27-28}	0.9663	0.9695	0.9781
Q_{c10}	5.0000	1.5543	2.5433
Q_{c12}	1.5065	1.4242	4.0442
Q_{c15}	3.9931	2.5205	5.0000
Q_{c17}	3.7785	1.6400	0.0000
Q_{c20}	3.2593	5.0000	4.7873
Q_{c21}	4.1425	1.8539	4.8628
Q_{c23}	4.9820	3.3035	5.0000
Q_{c24}	4.5450	4.5941	5.0000
Q_{c29}	4.1272	3.5062	4.5742

Table A3. Best solutions by PSO methods for the IEEE 30-bus system with objective of stability index

Variables	PSO-TVAC	HPSO-TVAC	ABC
V_{g1}	1.1000	1.0979	1.1000
V_{g2}	1.0934	1.0997	1.0947
V_{g5}	1.0969	1.0500	1.1000
V_{g8}	1.0970	1.0663	1.0884
V_{g11}	1.1000	1.0561	1.1000
V_{g13}	1.1000	1.0886	1.0983
T_{6-9}	1.0935	0.9939	0.9821
T_{6-10}	0.9000	1.0150	0.9552
T_{4-12}	0.9579	0.9121	0.9753
T_{27-28}	0.9651	0.9406	0.9816
Q_{c10}	3.1409	3.7685	5.0000
Q_{c12}	3.0186	4.6323	3.4219
Q_{c15}	1.4347	2.6542	3.0048
Q_{c17}	3.8498	2.6897	3.8582
Q_{c20}	0.0000	2.8806	0.0000
Q_{c21}	5.0000	2.1071	5.0000
Q_{c23}	0.0000	3.1044	4.9760
Q_{c24}	2.1733	2.1797	4.7488
Q_{c29}	2.2708	3.5843	5.0000

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