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Intelligent operation of thermal storage systems based heat pump pool for cost efficiency

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***Abstract*—The customers in the rural areas experience high heating costs than in the cities. The flexibility offered by the heat pumps (HP) and increasing the renewable energy sources (RES) share can play a key role in providing cheap heat without affecting the customer comfort preferences. This paper proposed a genetic algorithm based optimal heat consumption of individual households as a pool for minimizing the energy cost. The smart models of heat pump (HP) and phase change material (PCM) based heat storage systems are developed. These models are simulated for a cluster of 20 households having solar installations with different heat consumption behaviors that are located in a selected rural area i.e., Skive municipality in North Jutland, Denmark. The thermal units are intelligently coordinated by utilizing the electricity during periods of low price and excess production from local renewable resources including solar-photovoltaic (PV), thereby estimating the optimal heat consumption profiles. This study is simulated in DIgSILENT powerfactory and optimization routine from Matlab is utilised, which demonstrates the control of flexible HP units for balancing the local generation.**

I. Introduction

Electric heating is a key factor for reaching the goal set for low-carbon energy system [1]. This goal mainly entails the integration of renewable energy resources (RES) including wind, solar-PV and using electricity for heating (heat pumps) and transport (electric vehicles). Consequently, heat pumps are considered as quintessential infrastructure due to their flexible consumption feature that has the potential not only to reduce the individual household energy consumption cost but also increase the penetration of local RES production. In general, the residential HPs are relatively small electrical loads ranging from 3 - 10 kW_{el}. For actively participating in the electricity market requires higher capacities in order to reap the economic benefits, which can be achieved by the aggregation of HP pools [2]. Aggregators stack the flexibility of the individual consumers into registry of devices that are to be directly controlled depending upon the objectives such as low electricity price periods, high renewable production etc [3]. The thermal demand consisting of space heating (SH) and domestic hot water, where the SH can be shifted without giving thermal discomfort to the occupants as the building thermal inertia offers slow dynamics [4]. In addition, HPs installed along with hot water storage tank (HWST) decouples the heat that is produced to actual heat demand increasing the degree of flexibility of HP operation [5]. There are many research activities that are taking place in the field of thermal energy storage systems (TESS) in transmission and distribution applications [6]. There are various forms of TESS including sensible heat, latent heat etc., where latent heat storage technology using phase change material (PCM) has the property of high storage density making it most attractive than the other forms for many applications. A PCM is a substance that either releases or absorbs a lot of heat energy while changing the state from solid to liquid at a constant temperature. In [7], PCM based TESS has been employed for smart energy management in the building in order to not only minimize the electricity consumption but also meet the indoor temperature requirements. Moreover, the latent heat based thermal storage systems improves the life of HP by reducing the number of start and stop times, especially when the demand for heat is very low.

Heat demand from the majority of the households in Denmark is met by the district heating (DH) system supported by combined heat and power plants. Other technologies including electric boiler, heat pumps, waste to energy etc are being used to a lesser degree. However, the electric heating is expected to increase with the raise in the share of renewable energy. It is important to develop control methodology for harnessing the benefits from the synergistic cooperation between power and heating systems. This paper proposes the intelligent control of heat pump pool consisting of 20 households in Skive municipality, Denmark. The smart models of heat pump and PCM based thermal storage systems that can be used to optimize the energy consumption within the household are modeled in the DIgSILENT software. The storage tank works in concurrence with HP, thereby absorbing the heat while charging and recovery of heat takes place during discharging process. The real data of thermal demand of these households is used to set the comfort set points and also in deriving the new consumption patterns meeting the necessary constraints. The paper is organized in six sections, where the literature is discussed in the introduction followed by modeling of assets then the data is analysed. The remaining sections include the proposed methodology, the simulation results and finally the conclusions from the proposed work.

II. Smart models of assets

The schematic diagram of thermal energy storage based HP system is as shown in Figure 1, where the main components are an air-source heat pump (consisting of a compressor, a condenser and an evaporator) and PCM based storage tank. The two key performance indices are the total energy usage and charge/discharge time that are affected by the outdoor temperature. The electricity consumption in the heating systems is needed for both heat pump and water pump. Moreover, the charging process associated with PCM technology is non-linear unlike sensible heat technology. The working of HP is that it collects heat from the ambient air and transfers the heat into cycling water, which in turn is delivered to storage tank. The heat transfer fluid is considered to be water in this work.

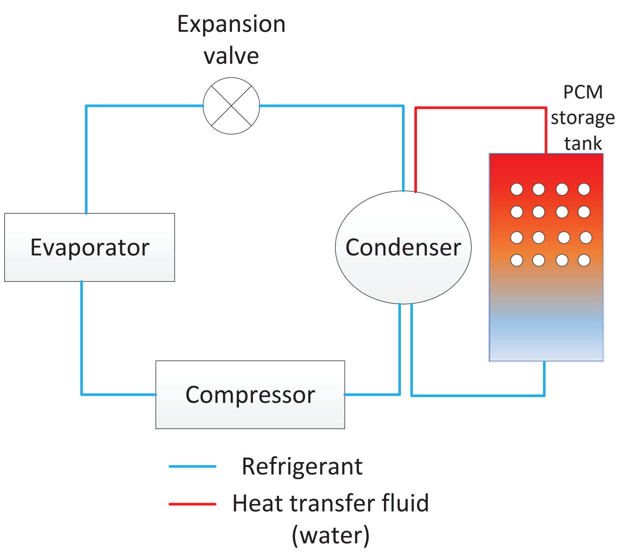

Fig. 1. Schematic of TESS based HP

A. HP model

The heat pumps are rated at 2.5 kW with a power factor of 0.98 lag. Assuming a constant speed compressor drives the unit, a soft starter is modelled based on the work given in the reference [8]. This model limits the starting current to two times its nominal, a second after it is turned ON. The delays associated with the compressor dynamics are also included. Accordingly, the thermal power produced by HP (Q_{HP}) is calculated from the real power rating (P_{HP}), coefficient of performance (COP) and time delay (T_d) in the HP operation and is as given in the Equation 1.

$$Q_{HP} = P_{HP} * C_s * COP * T_d \tag{1}$$

The time that is needed for HP to produce the output thermal power after it is switched ON is considered to be as 15 mins, which is generic for most of the installations. The COP depends on the ambient temperature and the control signal (C_s) defines the activation of HP upon availability of RES generation and low electricity prices in the power grid. The energy provided by the HP can be estimated as given in the Equation 2.

$$E_{HP} = \frac{1}{3600} * \int Q_{HP} dt \tag{2}$$

In order to avoid a kind of bacteria that grow below certain temperature within the storage tank, the HP is controlled based on hysteresis control with upper band to switch it OFF and lower band to switch it ON. The parameters associated with HP are given in the Table I.

TABLE I
HP PARAMTERS

Parameters	Values
Power rating	2.5 kW
Storage volume	300 l
Height	1.475 m
Height	7 kWh

B. PCM based storage model

Different shapes including balls, sticks etc., are being used in salt-hydrate based phase change materials, which are characterised by high latent heat of fusion. When it solidifies the heat is being stored and releases the heat during melting state. In the current study, ball shaped PCM is considered. A simple one dimensional model is used to determine the temperature distribution in the tank and the following assumptions are made.

- The tank is perfectly insulated.
- Heat loss from tank to surrounding is neglected.
- The inlet temperature of HTF is constant during the entire charging and discharging processes.
- Radiant heat transfer is neglected.
- The initial temperatures of both the HTF and PCM are uniform.

The energy balance is as given in the Equation 3. The term on the left hand gives the total energy stored over a time step with C_f being the fluid heat capacity. The first term on the right hand represents the energy transfer to control volume through advection with $\dot{m}$, c_{pf} being mass flow rate of HTF and specific heat capacity at constant pressure, respectively. Furthermore, the next right hand term is the net rate of energy exchanged between PCM capsule and fluid though convection, where h_f is heat transfer coefficient, A_f is the surface area of the exchange, T_f is the fluid temperature and T_{PCM} is the temperature at the wall of the PCM capsule.

$$\frac{dT_f}{dt} * C_{pl} = \dot{m} * c_{pf} * (T_{in} - T_{out}) + h_f * A_f * (T_{pcm} - T_f) \tag{3}$$

The PCM properties that are considered in this work are listed in the Table II. The melting temperature for PCM is 58^0 C, the intial temperature in the tank is 60^0 C and the latent heat of fusion is 338 kJ/kg.

TABLE II
PCM PROPERTIES [11]

Properties	Solid	Liquid
Specific heat [kJ/kg-°C]	4.226	1.762
Density [kg/m3]	1000	1000
Thermal conductivity [W/m-°C]	0.556	2.22

C. Solar-PV model

The power input for the heat pump is extracted from the excess energy from the renewable generation sources (RES) such as solar and wind both at household and community level. In addition, grid energy is also used when the electricity prices are low. For the present work, solar-PV is considered and modeled in DIgSILENT, and the respective model is as following. The active power output of a single PV system, i.e., an array of panels connected to the grid through a single inverter is calculated based on irradiance input data is given in the following Equation 4 [9], where E_g is the global irradiance (W/m^2), $P_{pk,panel}$ is the peak power of solar panel (kW), η_{rel} is the relative efficiency of the panel, η_{inv} is the inverter efficiency, n_{panel} is the numer of panels per inverter and E_{STD} is the standard irradiance (1000 W/m^2).

$$P_{PV} = \frac{E_g * E_{pk,panel} * \eta_{rel} * \eta_{inv} * n_{panel}}{E_{STD}} \quad (4)$$

III. DATA ANALYSIS

The total thermal demand consumption data for 20 households for year 2019 is as shown in Figure 2. It can be observed from the thermal demand profile, the thermal demand is highly varying in the first part and last part of the year, and it is low in the summer months of Jun, Jul and Aug, which is agreeable according to the weather conditions. The Elspot prices from Energinet's data hub [11] for the year 2019 is as shown in Figure 2. It can be observed that the spot prices are highest in the month of January and went to a greater number of times to negative in the month of March. Further from Figure 2, it can be clear that the month of March witnessed high thermal demand. Considering this peak demand period, March month would be a good business case, where electricity price is at its low and it is always advantageous to use the locally generated RES production for meeting most of the thermal demand. Figure 4 shows the total solar-PV production, total thermal demand from the 20 households and corresponding electricity spot prices for Mar 11 2019.

IV. PROPOSED CONTROL ALGORITHM

The problem formulation is as given in the Equation 5.

$$\begin{aligned} Min \quad & \sum_t [H_{ED}(t) - H_{Gex}(t)] * Elspot(t) \\ s.t \quad & H_{ED}(t) \leq H_{TD}(t)/COP \\ & SOE_{min} \leq SOE_t \leq SOE_{max} \\ & 21^0C \leq T_H \leq 23^0C \end{aligned} \quad (5)$$

The objective is to optimize electricity consumption towards HP in individual households along with its storage system by

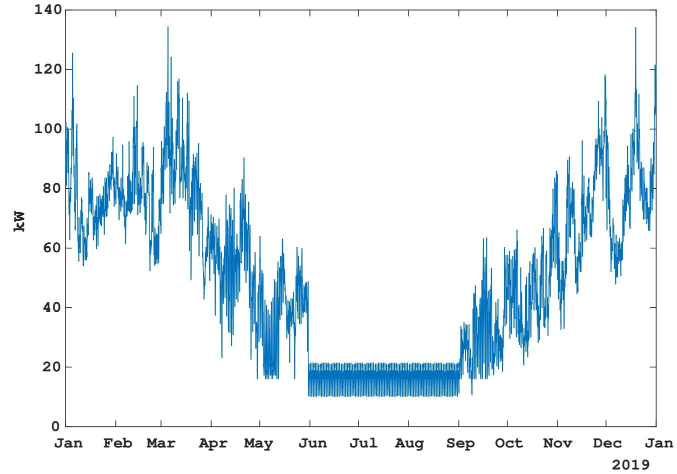

Fig. 2. Aggregated thermal demand of 20 households

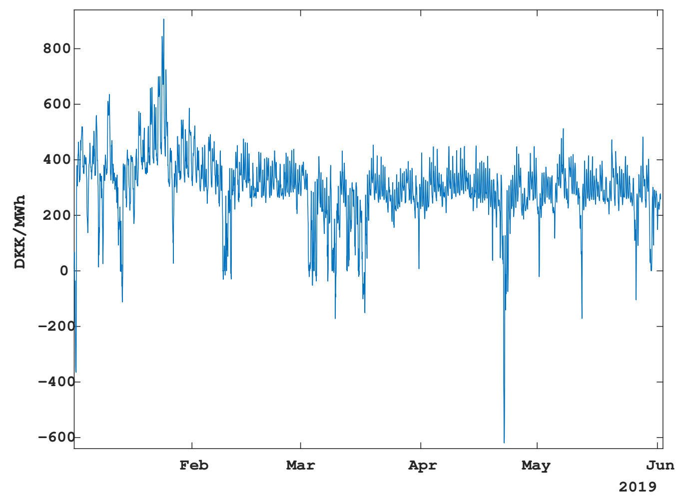

Fig. 3. Elspot prices for DK1

utilizing the excess generation from local solar-PV installation. The variables (H_{ED}) are optimal electricity consumption profiles that can take mixed integer values and the problem is non-linear in nature, thereby the genetic algorithm is chosen to solve the problem. The local controller associated with the HP's at consumer site provides the state of HP, state of energy (SOE) of the storage tank to the central controller that coordinates all the households. The key deciding factors used for scheduling the HP systems within the selected households are meeting the consumer comfort (inside temperature T_H), utilizing excess generation from local RES (H_{Gex}) and exploit the periods with low electricity prices ($Elspot$) of power grid. In addition, the constraints on the storage tank minimum and maximum energy levels, HP operational dynamics are also considered. The schematic of the proposed method is as shown in Figure 5. The results are presented in the following section.

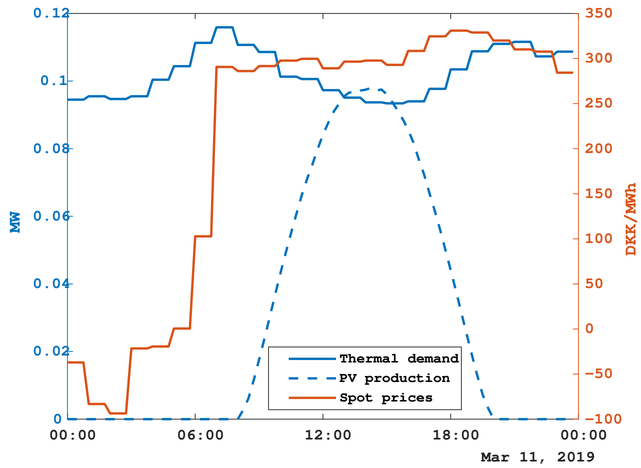

Fig. 4. Total solar-PV production and total thermal demand for 20 households pool

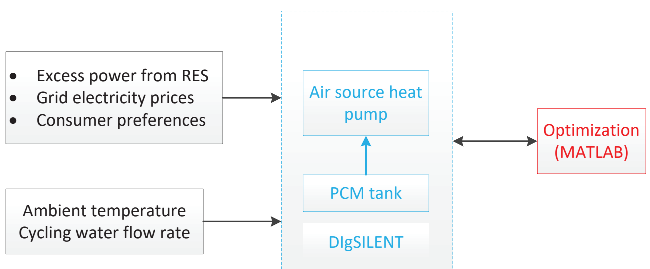

Fig. 5. Schematic of the proposed method

V. Simulation Results

The results are demonstrated for the selected day i.e., Mar 11^{th}, where the thermal demand witnesses peak, so it is interesting to find optimal consumption profiles that gains a cost efficient operation. The optimal thermal demand profiles are shown in Figure 6, corresponding to the 20 households. It is to be observed that there are two large peaks coming before and after 6 a.m., which are sharing the demand in a way that one peak falls in low electricity price zone from grid and other one in unavoidable peak tariff range. The optimal real power consumption profiles obtained from the genetic algorithm are as shown in Figure 7 corresponding to all the households. The profiles corresponding to one household towards HP output and thermal storage tank temperature are shown in Figures 8 & 9. It is to be noted that the thermal output of smart HP model has followed the 15 mins delay after it has been switched-ON. The COP is taken as 2.3 as per the considered simulation day i.e., Mar 11^{th}. The HP is switched ON in four continuous operating zones, one in late night,

The temperature inside the tank is maintained between ranges of 40 – 60 degrees, melting temperature for PCM is being 58^0 and can be observed from Figure 9 that the temper-

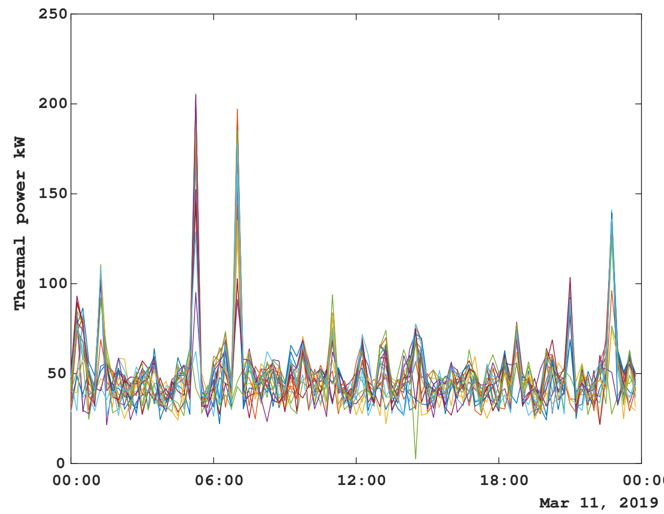

Fig. 6. Optimal thermal demand profiles

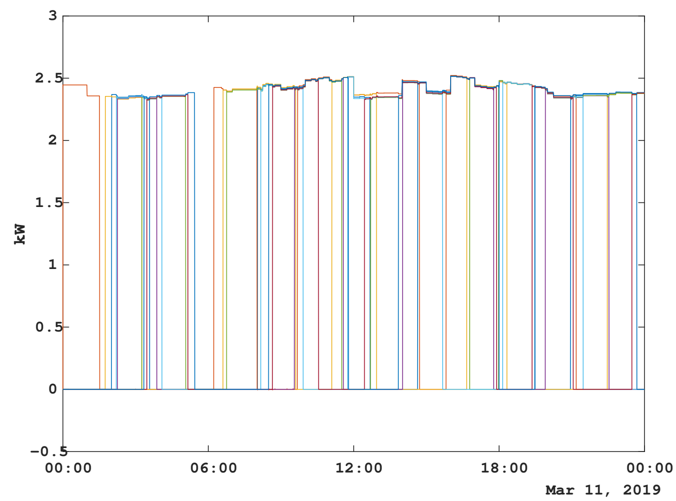

Fig. 7. Optimal operation of HPs of 20 households

ature is reaching the minimum range due to thermal demand peaks during morning and late evenings. Further, the storage is being charged from the on-site solar-PV excess production at the households during 9am – 5 pm. The peculiarity of the PCM based storage tank is that the non-linearity of the phase changing process with respect to the temperature inside the tank. The initial temperature is at 60^0, where the PCM is in liquid state i.e., discharging. While temperature falls below 58^0 the PCM starts solidifying i.e., charging by absorbing energy, which took place during the first half of the day and an hour in the evening. The fitness function is the total cost that is paid towards heat consumption by this household pool is given in the Table III, which is evident that the payment by the pool towards meeting thermal demand has considerable reduced when compared to the case without intelligent control of HP.

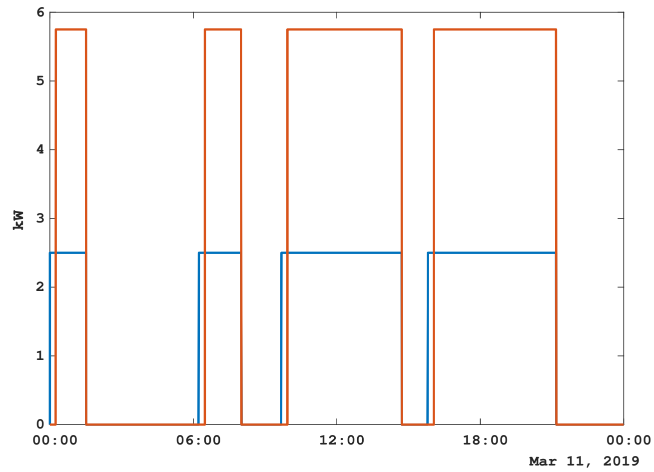

Fig. 8. Electrical and thermal powers of HP for a household

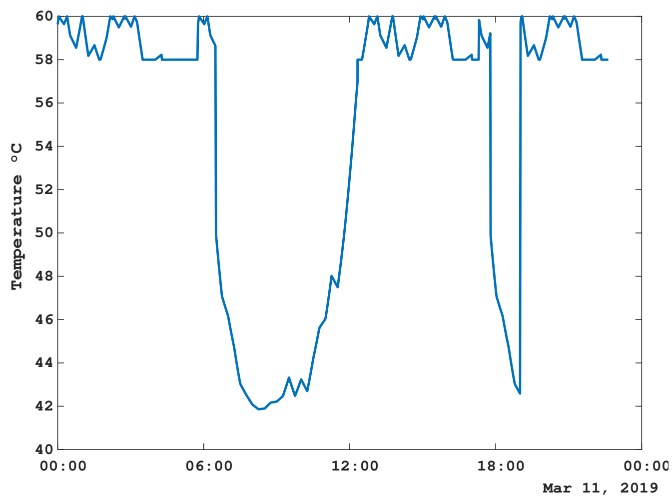

Fig. 9. Temperature inside the storage tank for a household

TABLE III
ELECTRICITY BILL TOWARDS HOUSEHOLD POOL HEAT CONSUMPTION

Without HP control	With HP control
388.68 DKK	262.93 DKK

VI. Conclusion

The smart models of HP and PCM based thermal storage tank are developed. The electricity consumption towards individual household as a pool is optimized for minimizing the cost and also increasing the share of on-site solar-PV generation. The results demonstrates the benefits of using latent heat technology based storage to shift most of the heating loads to off-peak periods, where the electricity cost is cheaper. The fossil fuel based traditional district heating systems that are most common in EU countries needed to be replaced with electric heating by availing the benefits of local or community based RES generation possibilities. In order to actively participate in the electricity markets, it is necessary to create pools in every locality and aggregating them into clusters, thereby increasing the flexibility resulting in the cost efficient operation, which is illustrated in the present work.

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