Cyclic Blackout Mitigation and Prevention

by

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A Doctoral Thesis submitted in fulfilment of the requirements
for the award of the degree of

Doctor of Philosophy (PhD)

Electronic and Electrical Engineering Department

Faculty of Engineering,

University of Strathclyde

Glasgow, UK

2015

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Declaration

This Thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which led to the award of a degree.

Kasim Al-Salim

Dedication

To you[1] … my little teacher
whom I haven't known … yet you taught me a lot
Taught me to do my best against all odds
without balking my obligations,
abandoning my dreams, or
doing my chores except in the best way I can.
Sincerely I hope that someday I will meet you…
just to say:
Thank you for being such an inspiration …
Thank you my little teacher

Kasim Al-Salim

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[1] This is the picture of a 7 year old Syrian child taken in 2007 while focusing on doing her homework passionately despite the cold weather while she was selling some simple food in her primitive kiosk on one of the streets in Damascus, Syria. This picture was taken by photographer Waseem Khair Baik and won the 'Best Arab picture award' in 2007 awarded by the Federation of Arab News Agencies. The photographer said that this girl always covered her face to prevent him from taking her picture, so he took it from a 30 m distance. This picture has inspired millions of people to gain knowledge at all cost without abandoning their responsibilities and obligations struggling to the end for a better future. Feel the commitment this child has towards her family and her deep understanding of their critical financial situation, notice the fine arrangement of goods, the display angles of the last row of food, and the even distribution of food to have a simple idea how this child is well organised and intelligent, and finally note how much she is focusing on her study without being distracted by her natural passion as a child to play or just to look on what's happening in the street.

بسم الله الرحمن الرحيم

Acknowledgements

A PhD seems to be an individual endeavour but it isn’t. It is more akin to a fruitful tree the fruits are seen but the roots are not.

At the very beginning, and before anyone, I want to deeply and humbly thank you dear Allah, my one and only God, for all your help and guidance throughout the period of my life and study without which this work was not possible.

I also extend my deepest gratitude to the following, whose unconditional belief, help and support have kept me motivated and made this work possible: First and foremost I wish to thank Professor Ivan Andonovic, for his guidance, understanding, and support as my first supervisor. I also deeply thank Dr Craig Michie for his support during critical moments. I would like to express my gratitude to Dr Jun Hong and Dr Bruce Stephen for their lucid and stimulating discussions. Special thanks must go to Dr Lina Stankovic, Dr Vladimir Stankovic, Dr Mahmoud Beshr, and Dr Jing Liao for their support and discussions. Miss Morag Aitkens is memorable not only for her prompt support but also for her kindness. I cannot forget all the other PhD students and CIDCOM members for their useful discussion, friendship, and advice. Finally, sincere thanks and appreciation go to my kind neighbour and language master Mr. Peter McEnerny for his generous help in fine tuning this thesis.

It is in Iraq where the most basic source of my life energy resides: my family. I have an amazing family, unique in many ways, and the stereotype of a perfect family in many others. Their support has been unconditional all these years; they have given up many things for me to be at University of Strathclyde; they have cherished with me every great moment and supported me whenever I needed it, and although the scientific knowledge is mine, the success is ours.

في البداية احب ان اقول ان جهدا كبيرا مثل دراسة الدكتوراه قد يبدو للوهلة الاولي عمل شخص واحد ولكنه في الحقيقة ليس كذلك ... انه كالشجرة المثمرة .... الثمار يمكن رؤيتها لكن الجذور تبقى خفية....

في البداية يجب علي ان اشكر من له الفضل كله في انجاز هذا العمل في كل مراحله وتفاصيله وهو الله سبحانه وتعالى الذي فضله علي لا يعد ونعمه علي لا تحصى فبدون عونه في كل وقت وحين وهدايته لي لما فيه خيري وتسخيره الصعب الذي لا يُدخل وتمهيده الوعر الذي لا يُسلك وتقريبه البعيد القاصي وارشادي للدقيق الخافي وترتيب امري كله لما كنت انا ولا كان هذا العمل، اللهم فلك الحمد قبل كل احد، حمدا كثيرا طيبا مباركا فيه، عدد خلقك ورضا نفسك وزنة عرشك ومداد كلماتك، ولك الشكر قبل كل مخلوق على كل ما تفضلت به علي، فلم تتخل عني رغم غناك عني وفقري اليك وكثرة ذنوبي لا اله الا انت وحدك لاشريك ولا مثيل لك.

ومن بعد، يجب علي ان لا انسى من غابا عني بجسديهما ولكن بقيت روحهما خفاقة حولي، واختفى صوتهما ولكن بقيت كلماتهما ترن في اذني، واختفت صورتهما لكن بقيا يعيشان في قلبي، والدي الفاضل عبد القادر صالح السالم ووالدتي الغالية اللذان علماني وربياني ووضعوا الاساس لكل هذا الانجاز جعل الله ثواب هذا العمل في ميزان حسناتكما واسكنكما فسيح جناته ولم ينقص من فرحة انجاز هذا العمل الا متعة وضعه بين يديكما.

ثم اتوجه بالشكر والعرفان الى اسرتي (زوجتى الحبيبة واولادي الغالين ياسمين وعبدالله وندى ومحمد وايمان) الذين تحملوا الكثير والكثير اثناء بقائهم في العراق طوال السنوات الماضية، والى الدمعات الغالية التي سكبتها عيونهم في لحظات الوداع، والى الآهات التي تكسرت في صدورهم في سنين الفراق، والى الابتسامات الساحرة التى تزينت بها شفاههم اثناء لحظات اللقاء، كنتم مصدر قوتي وسعادتي وفخري وتقديري، فجزاكم الله خير الجزاء، وكما شاركتم بالصبر اسأل الله ان يشرككم بالاجر، واعلموا انه رغم كون المعرفة العلمية هي لي لكن النجاح لنا جميعا.

ويتطلب العرفان مني ان اتقدم بشكري الخالص الى الحكومة العراقية ممثلة بشخص السيد رئيس الوزراء د. حيدرالعبادي والى وزارة التعليم العالي والبحث العلمي ممثلة بشخص وزيرها الدكتور حسين الشهرستاني و دائرة البعثات العراقية ممثلة بكادرها ورئاسة جامعة البصرة ممثلة بكاردها واخص منهم بالذكر د. باسم عبدالعزيز العثمان من كلية الاداب وعمادة كلية العلوم وقسم علوم الحاسبات تدريسيين وخدمات واخص منهم بالذكر د.حميد عبدالكريم يونس ود.حيدر محمد ود.ميثم ابوالهيل ومن قسم الرياضيات اشكر د.عقيل جاسم حرفش والى كادر الملحقية الثقافية العراقية في لندن كلهم واخص منهم بالذكر الاخ الطيب علي الربيعي المسؤول الاداري لملفي على دعمهم ورعايتهم وتشجيعهم المستمر.

كذلك يطيب لي ان اشكر وزارة الكهرباء العراقية ممثلة بكوادر مديرياتها المختلفة في البصرة، واخص منهم بالذكر الاخوة وسام سليم ومنذر عبد الامير من محطة الكفاءات الفرعية، على تعاونهم وعلى المعلومات والخرائط والبيانات التي زودوني بها فلهم مني كل الشكر والتقدير والثناء وجزاكم الله خيرا.

كما يقتضي الوفاء مني ان اشكر واحيي الجنود المجهولين اصحاب القلوب الطيبة والانفس الزكية من اقربائي واحبتي وكفلائي واصدقائي ومعارفي وطلبتي الغالين الذين ساندوني طوال فترة دراستي وزرعوا الامل في نفسي في اللحظات العصيبة ووقفوا الى جانبي عونا وتشجيعا وتثبيتا ومؤازرة ودعاءا اثناء فترات دراستي وهوني علي وحشة الغربة ومشقتها واضاؤوا النور في اخر النفق فان كان المجال لا يسع لذكركم اجمعين فقد

وسعكم قلبي محبة وعرفانا فاسأل الله عز وجل ان يجعل ذلك في ميزان حسناتهم فقد كنتم في غاية الوفاء وجزاكم الله خير الجزاء.

ولايتم الشكر الا بشكر جميع العراقيين فردا فردا بدون تمييز ولااستثناء، الذين احسنوا بنا الظن فابتعثونا في الوقت الصعب، فجزاهم الله عنا خير الجزاء، وفقنا الله جميعا لخدمتهم بكل تواضع، ونفعهم بكل علم تعلمناه، وان ننقل اليهم كل مفيد رأيناه، وان نعلم ابناؤهم بكل اخلاص كما اقتطع اباؤهم من قوتهم ليعلمونا في وقت الشدة.

وختاما يتوق لي ان احيي كل الطلبة العراقيين الدارسين في خارج العراق (بعثات وزمالات ونفقة خاصة) فردا فردا من اعرفهم ومن لا اعرفهم لشجاعتهم وصبرهم ومصابرتهم واصرارهم وتضحياتهم وحبهم للعلم وابداعهم رغم قساوة الظروف في الداخل والخارج. اسأل الله عز في ملكه وجل في علاه ان يوفقنا لخير العباد والبلاد.

وكما بدأت بحمد الله مستحق الحمد والثناء عز في ملكه وجل في علاه لايليق ان اختم الا بحمده
فالحمد لله الفرد الصمد الذي بحمده تتم الصالحات وبشكره تدوم الاعطيات وبذكره تطيب الحياة
الذي جعل معجزة رسوله الكريم (كتابا) لا تنتهي معجزاته بدأه بـ(اقرأ) وانهاه بـ(اكملت)
وصلى الله وسلم وبارك على الرحمة المهداة الهادي البشير خاتم الانبياء والمرسلين
حبيبنا وقائدنا وقرة عيوننا ابا القاسم سيدنا محمد (صلى الله عليه واله وسلم)
وعلى مصابيح الهدى وسفن النجاة الهداة المهديين آله الطيبين الاطهار
وعلى اصحابه الطيبين بناة حضارة الاسلام وناشريه في الامصار
وعلى جميع عباد الله الذين اصطفى من الصالحين الاخيار

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Abstract

Severe and long-lasting power shortages plague many countries, resulting in cyclic blackouts affecting the life of millions of people. This research focuses on the design, development and evolution of a computer-controlled system for chronic cyclic blackouts mitigation based on the use of an agent-based distributed power management system integrating Supply Demand Matching (SDM) with the dynamic management of Heat, Ventilation, and Air Conditioning (HVAC) appliances. The principle is supported through interlocking different types of HVAC appliances within an adaptive cluster, the composition of which is dynamically updated according to the level of power secured from aggregating the surplus power from underutilised standby generation which is assumed to be changing throughout the day. The surplus power aggregation provides a dynamically changing flow, used to power a basic set of appliances and one HVAC per household.

The proposed solution has two modes, cyclic blackout mitigation and prevention modes, selecting either one depends on the size of the power shortage. If the power shortage is severe, the system works in its cyclic blackout mitigation mode during the power OFF periods of a cyclic blackout. The system changes the composition of the HVAC cluster so that its demand added to the demand of basic household appliances matches the amount of secured supply. The system provides the best possible air conditioning/cooling service and distributes the usage right and duration of each type of HVAC appliance either equally among all houses or according to house temperature. However if the power shortage is limited and centred around the peak, the system works in its prevention mode, in such case, the system trades a minimum number of operational air conditioners (ACs) with air cooling counterparts in so doing reducing the overall demand.

The solution assumes the use of a new breed of smart meters, suggested in this research, capable of dynamically rationing power provided to each household through a centrally specified power allocation for each family. This smart meter dynamically monitors each customer’s demand and ensures their allocation is never exceeded.

The system implementation is evaluated utilising input power usage patterns collected through a field survey conducted in a residential quarter in Basra City, Iraq. The results of the mapping formed the foundation for a residential demand generator integrated in a custom platform (DDSM-IDEA) built as the development environment dedicated for implementing and evaluating the power management strategies. Simulation results show that the proposed solution provides an equitably distributed, comfortable quality of life level during cyclic blackout periods.

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LIST OF ABBREVIATIONS

τ : Ambient temperature (τmin $\leq \tau \leq$ τmax)
τmax : Maximum allowable operating temperature
τmin : Minimum allowable operating temperature
p^{at} : Total demand of all covered ACs
p^{ct} : Total demand of all covered COs
p^{mt} : Total demand of all covered MFs
p^{sn} : Snooped power
A^q : AC set hosting all AC appliances in residential quarter (q)
A^s : A subset of set A^q
C^q : CO set hosting all AC appliances in residential quarter (q)
C^s : A subset of set C^q
M^q : MF set hosting all AC appliances in residential quarter (q)
M^s : A subset of set M^q
P^{com} : Power generated by commercial generator number
P^{cri} : Power generated by critical generator number
P^{cust} : Customer demand
P^{dom} : Power generated by domestic generator number
P^{dxloss} : Distribution system power losses
P^{grid} : Grid power
P^{pub} : Power generated by public generator number
P^{sb} : Standby power
P^{sbres} : Standby generation reserve
P^{txloss} : Transmission system power losses
P^{ures} : Utility reserve
P^{util} : Utility power
a_h^q : A single AC appliance
c_h^q : A single CO appliance
m_h^q : A single MF appliance
AA : Administrative Agent
AC : Air Conditioner
ap : Electric appliance, device, or instrument
ARDG : Abstract Residential Demand generator
BPMN : Business Process Modelling Notation
BS : Basic Set
BUG : Backup generator
$Ca_{a,h}$: Final aggregate of all control action that are applied to the appliance in order to control its power consumption.
CB : Circuit Breaker
CBM : Cyclic Blackout Mitigation
CEMS : Community Energy Management System

CFC : Chlorofluorocarbons
CFL : Compact Fluorescent Lamps
CH : Cluster Head
CHP : Combined Heat and Power
CIC : Command Identification Code
CO : Evaporative Air cooler
CPP : Critical Peak Pricing
D : the powered set of covered HVAC appliances
dce : Demand Consuming Entity (e.g. house)
DDSM : Distributed Demand Side Management
DER : Distributed Energy Resources
DES : Distributed Energy Storage
DG : Distributed Generation
DKB : Dynamic Knowledge Base
dl : Distribution losses
DLC : Direct Load Control
DNO : Distribution Network Operator
DOE : US Department of Energy
DR : Demand Response
DSG : Dispatchable Standby Generation
DSM : Demand Side Management
DVP : Dominion Virginia Power
EE : Energy Efficiency
ESS : Energy Storage System
FIPA : Foundation for Intelligent Physical Agents
FRIENDS : Flexible, Reliable and Intelligent Electrical eNergy Delivery System
FS : Fair Share
FSM : Finite State Machine
GA : Generation Agent
Gc : Total number of commercial standby generators
GC : Generation Controller
Gd : Total number of domestic standby generators
GDP : Gross Domestic Product
GESS : Composite Energy Storage System
GHG : Green House Gases
GIC : Generator Interfacing Controller
Gn : Number of generators in the targeted power plant
Gp : Total number of public standby generators
Gr : Total number of high priority standby generators
Gs : Standby generation facility
Gu : Number of utility generation plants
GUI : Graphical User Interface
H : Ambient humidity ($h_{\mathbf{min}} \le h \le h_{\mathbf{max}}$)
HA : House Agent

HEMS : Home Energy Management Systems
HFC : Hydrofluorocarbons
HLC : House Local Controller
H_{max} : Maximum allowable operating humidity
H_{min} : Minimum allowable operating humidity
HPWH : Heat Pump Water Heater
HSF : HVAC Service Factor
HTUP : HVAC Total Usage Period
HVAC : Heating, Ventilation, and Air Conditioning
ICT : Information and Communication Technology
IDAPS : Intelligent Distributed Autonomous Power System
IDE : Integrated Development Environment
IDEA : Integrated Development Environment with Agents
IDG : Interactive Distributed Generation
ISO : Independent System Operator
LC : Local Controller
LED : Light Emitting Diode
LEE : Least Enthalpy Estimation
lo : Number of local standby generators in the same facility
LSE : Load Serving Entity
LVDN : Low Voltage Distribution Network
MAS : Multi-Agent System
MCC : Micro-grid Central Controller
MF : Mist fan
MO : Market Operator
MS : Micro-Source
MSC : Main System Controller
$Na_{a,h}$: Number of appliance of type (a) in a house (h).
NECPA : U.S. National Energy Conservation Policy Act
NETL : National Energy Technology Laboratory
NRDG Non-Residential Distributed Generation
nsbres : Number of available standby reserves
nures : Number of available utility reserves
NYISO-EDRP : New York Independent System Operator-Emergency DR Program
OECD : Organization for Economic Co-operation and Development
$Pa_{a,h}$: is the power of the specified appliance (a) in house (h)
PANDA : Power Aggregation aNd Demand Appeasement
PCBB : Power Converter Building Block
PCC : Point of Current coupling
PGE : Portland General Electric
PHEV : Plug-in Hybrid Electric Vehicle
PR : Ramp Period
PV : Photovoltaic
q : Residential quarter

QCC	:	Quality Control Centre
QoE	:	Quality of Experience
QoS	:	Quality of Service
RC	:	Regional control
REN	:	Renewables
RP	:	Ramp Period
RSM	:	Rationing Smart Meter
RTFS	:	Real-Time Digital Simulator
RTO	:	Regional Transmission Organization
RTP	:	Real Time Pricing
SAIC	:	Science Applications International Corporation
SC	:	Schedule Coordination
SCADA	:	supervisory control and data acquisition
SDM	:	Supply Demand Matching
SKB	:	Static Knowledge Base
SOC	:	South Oil Company
SR	:	Spinning Reserve
SRP	:	Sustained Response Period
STOR	:	Short Term Operating Reserve
t	:	Time slot number ($t=1,2,3,\ldots,T_{\mathbf{Blackout}}$)
$T_{\mathbf{blackout}}$	:	Length of the cyclic blackout period
tl	:	Transmission losses
ToU	:	Time of Use
TT	:	Temperature Triggered
UA	:	Utility Agent
UIC	:	Utility Interfacing Controller
UPS	:	Uninterruptable Power Supply
VPP	:	Virtual Power Plants
WACLSS	:	West-bank AC Load Shedding System

Chapter One
Introduction

1.1 Motivation

The current ongoing technological revolution has resulted in a strong dependency on electricity, essential to modern societies and to the health of economies. These dependencies coupled with the proliferation of a rich mix of new electrical appliances have resulted in an escalating demand which has created power shortages and blackouts throughout the world [1]. Power shortages are not confined solely to developing countries but occur across many societies. In the case of the former, shortages are a function of many factors such as inadequate power generation capacity, power transmission challenges, power system ageing, inappropriate tariffs and inefficient electricity use by consumers [2]. It is also a consequence of catastrophic events such as wars and conflicts as in Iraq resulting in chronic cyclic blackouts [3], [4]. On the other hand, during blackouts consumers are subject to temporary power shortages that last for hours to days owing to faults, weather and natural or man-made disasters [5].

The alarming trend is that the number of occurrences is increasing even in advanced power systems such as that servicing the USA; there were ~3,500 outages in 2014 alone affecting the daily life of ~14 million people, a 12% increase in the number of outages compared to 2013 [6]. The size of population affected by such power loss is growing to sizeable levels e.g. the 2011 occurrence in India, the largest power blackout in history, affected the daily life of nearly 700 million individuals [7].

Several solutions have been adopted to manage this challenge and to mitigate its impact amongst them is load shedding, often viewed as the last resort [8]. Among these solutions, building more and more power generation, transmission lines, and distribution networks seems to be inevitable yet such a solution is slow and requires substantial investments. In some cases the evolving demand outstrips the generation capacity during the building phases.

In war ravaged countries like Iraq, cyclic blackouts have hindered the pace of recovery and the quality of life for its population. Chronic cyclic blackouts have been a feature in everyday life since 1996 and still persist due to ever increasing demand continually outpacing new generation deployments. The situation becomes even more acute during summer when air conditioning becomes a necessity (the temperature can reach a maximum of 56°C [9]), causing discomfort and suffering. A number of measures have been proposed worldwide to solve such crises among those reinforcing power generation, transmission, and distribution system capabilities, raising appliance efficiency, controlling HVAC demand, making power more costly, reducing power generation and transmission losses, reducing electricity theft, full utilization of available standby generation. What remains a challenge and a requirement is a dedicated solution for managing cyclic blackouts.

1.2 Objective

The main objective of the research is to design a system founded on a supply-demand management and matching strategy aimed at mitigating and preventing cyclic blackouts, during which utility power is supplied for some hours and cut off during others, a cycle repeated continuously throughout a day. The approach maps basic household demand and provides optimum HVAC scheduling at minimum cost. The proposed solution works as a transitional strategy bridging the no-power gaps that currently prevail in cyclic blackouts until sufficient power generation from the utilities is secured.

Furthermore the case study targets cyclic blackouts prevalent in hot countries where air conditioning is a necessity even though it represents the major component of consumption in overall demand. Thus air conditioning demand is the root on which the proposed solution manages the OFF periods in blackouts as needed in so doing reducing the overall demand and enhancing flexibility in setting and fine tuning demand management strategies [10].

The specific use case concerns a residential quarter in Basra, Iraq where the temperature can reach a 56°C high [9]. The proposed solution focuses on the residential sector because it attracts less attention in environments suffering from chronic power shortages; most effort is focused on other higher priority sectors such as health and essential backbone industries such as oil.

The solution is based on 'interlocking' several types of HVAC appliances with different power consumption and efficiencies and grouping them into one HVAC cluster. The cluster adapts an overall HVAC demand through changes in its mix in order to match the amount of surplus power secured from standby generation, distributed throughout and around the targeted residential areas. The technique can be extended to a prevention mode, managing power shortages through the application of the same clustering and dynamic HVAC composition but now matching not the amount of surplus power secured from standby generators but the amount of available level of utility power.

The design of a cyclic blackout mitigation and prevention system follows the following requirements and principles:

- capable of provisioning sufficient power to residential areas so that a basic set (BS) of appliances such as lights, fans, TVs, fridges and at least one air conditioning (or air cooling if the former is not possible) appliance can be operated during cyclic blackouts OFF periods. The proposed system takes advantage of the merits of air coolers, being more energy efficient than air conditioning since they can operate on a fraction of the power whilst providing a good level of air conditioning. Additional details on the merits of air cooling compared to air conditioning are provided in Section 3.4.1.
- with the minimum perturbation of the grid supply power ON/OFF schedules
- with no modification to the existing generation and transmission systems

- minimising all interfacing needed to connect the proposed system to the distribution network
- the number and type of allocated HVAC appliances depending solely on the amount of surplus power secured from available (underutilised) standby generation, not part of the grid's assets
- providing the best air conditioning/cooling service possible
- allocated HVAC usage time to be distributed fairly amongst all customers
- the financial burden on customers to be kept to a minimum

The verification of the strategy and its application is centered on a real-life case study, a residential quarter called 'Kafaat' in Basra. A field survey is undertaken at the outset to secure details of the environment and capture the influential factors contributing to the generation of its demand. The mapping includes knowledge of the types of used appliances, their distribution, family size, the profile/occupation of individual family members, and the willingness of customers to co-operate in any proposed solutions. In order to implement the suggested supply-demand strategy, the problem is decomposed into six major tasks:

- define the needed hardware infrastructure
- compose the supply-demand managing strategy
- design an abstract demand generator to provide the necessary test data
- create an integrated development environment to verify the proposed strategy and finally
- characterise the performance of the developed strategy

Different HVAC usage rights distribution techniques are examined. Furthermore, enhanced applications of the solution are developed to extend coverage and flexibility. Several scenarios are examined to assess the suitability of the solution under different power supply streams.

The proposed approach and associated applications for the selected case study are verified by simulation using a custom software platform. The generated abstract demand is the core test input to the validation, and the resulting outcomes are analysed. The limitations of the solution are highlighted, discussed and suitable solutions are suggested.

1.3 Contributions

The contributions of the research can be summarised as:

- the design and implementation of an intelligent distributed agent-based cyclic blackout mitigation strategy with the ability to cover basic household demand during cyclic blackout power OFF periods
- the design and implementation of a distributed agent-based cyclic blackout prevention strategy with the ability to effectively truncate peaks in demand thereby smoothing the overall profile
- the design and implementation of a dynamic HVAC adaptive clustering and interlocking algorithm which creates a heterogeneous dynamic cluster of interlocked HVAC appliances. The composition of the cluster and the mix of appliances change as the amount of available power changes
- a proposed functionality for a Rationing Smart Meter (RSM) as a means for monitoring customer power consumption and the capability to control the allocation and distribution of power during shortages
- creation of an open source Distributed Demand Side Management Integrated Development Environment with Agent support (DDSM-IDEA) platform to aid in the design and verification of power shortage management strategies
- the concept of abstract demand as a solution for demand profiles under scarce statistical data scenarios using finite state machines to describe a range of daily human activities seeded by significant field surveys. The basic set of activities overlaid over the active population of appliances infers overall demand
- a performance analysis and verification of the cyclic blackout mitigation and prevention system in its different modes of operation as a function of a number of power allocation schemes

1.4 Thesis Structure

The dissertation is segmented into nine main chapters.

Chapter 1 introduces the background to power shortages and various measures taken to overcome them. Chapter 2 summarises the approaches reported to address power shortages and the effectiveness of such measures. The aim is to provide a reference to the research through reported work in order to inform the development of the most appropriate solution.

An extensive survey of the current research in all the fields related to power shortage mitigation, supply-side and demand-side management is presented in Chapter 3. The supply-side focuses predominately on the utilisation of standby generation in covering the power deficiency while the demand-side covers the full range of research and development ranging from the control of air conditioning appliances to full system management. The conclusion drawn is that little research has addressed cyclic blackouts.

Chapter 4 presents in detail the proposed system and strategy underpinning the cyclic blackout mitigation mechanism. The solution is referred to as Power Aggregation aNd Demand Appeasement (PANDA) cyclic blackout mitigation. The chapter begins with a high level description of the system, followed by detailed descriptions of the main algorithms and the functionality of the RSM, the core implementation device used to monitor residential demand and to allocate power under a prescribed usage rights protocol.

In Chapter 5, details of the case study is given in order to provide a mapping of the city, its houses, its inhabitants, their power usage patterns and the available standby generation infrastructure. A field survey conducted to explore the socio-economic factors that affect any proposed cyclic blackout mitigation strategy is described. The survey also reveals the appliances in current use, their types and number in the surveyed households.

Chapter 6 describes the DDSM-IDEA platform developed to execute and verify the proposed cyclic blackout mitigation strategies. The platform possesses agent capabilities framed in a user-friendly graphical user interface (GUI) which accelerates platform mastering operations and reduces development and execution times.

Typical demand generation techniques are not applicable in the Iraqi case due to the unavailability of any statistical data that supports and validates the demand data generated by such techniques. This necessitated the development of an abstract residential demand that closely emulates typical Iraqi residential demand, used to execute and test the proposed strategies. The residential demand generation, integrated into the developed platform, is based on aggregating demand generated by various activities of different family members separately throughout the day related to their usage of available appliances. The overall residential demand is then the demand of all households.

Chapter 7 presents the results of the performance of the approach. The chapter includes the validation of these results through comparison with grouped air conditioning load shedding [11]. The system is extended to a prevention mode; Chapter 8 presents two extended applications, highlighting their limitations and suggesting suitable solutions.

Chapter 9 summarises the preceding chapters, draws conclusions and lists future work that enhances the concepts introduced by the research.

1.5 Publications

1.5.1 Journals

1. Kasim Al-Salim, Ivan Andonovic, Craig Michie, “Cyclic Blackout Mitigation and Prevention Using Semi-Dispatchable Standby Generation and Stratified Demand Dispatch”, *Journal of Sustainable Energy, Grids and Networks* (in press).

1.5.2 Conferences

1. Kasim Al-Salim, Ivan Andonovic, Craig Michie, “DDSM-IDEA: A Versatile Dual-Mode Distributed Demand Side Management Integrated Development Environment”, First International Conference on Systems Informatics, Modelling and Simulation, Sheffield, UK, 29th April-1st May 2014
2. Kasim Al-Salim, Ivan Andonovic, Craig Michie, “A Cyclic Blackout Mitigation System”, IEEE International Energy Conference, Dubrovnik, Croatia, 13th-16th May 2014
3. Kasim Al-Salim, Ivan Andonovic, Craig Michie, “The Impact of End User Behaviour on Blackout Creation and Mitigation; Case Study – Iraq”, BEHAVE Conference, Oxford, UK, 3rd-4th September 2014
4. Kasim Al-Salim, Ivan Andonovic, Craig Michie, “Wide Area Cyclic Blackout Mitigation by Supply-Demand Matching (SDM) of HVAC Counterpart Loads”, IEEE PES Innovative Smart Grid Technologies, Europe (ISGT 2014), Istanbul, Turkey, 12th-15th October 2014
5. Kasim Al-Salim, Ivan Andonovic, Craig Michie, “Cyclic Blackout Mitigation Using Rationing Smart Meters”, 6th International Renewable Energy Congress (IREC-2015), Sossue, Tunisia, 24-26 March 2015
6. Kasim Al-Salim, Ivan Andonovic, Craig Michie, “A Finite State based Residential Demand Generator for Scarce Statistical Data Scenarios”, 6th International Renewable Energy Congress (IREC-2015), Sossue, Tunisia, 24th-26th March 2015

7. Kasim Al-Salim, Ivan Andonovic, Craig Michie, “Cyclic Blackout Mitigation through HVAC Shifted Queue Optimization”, S. Klingert et al. (Eds.): E2DC2014, LNCS, Vol. 8945, pp34-51, 2015, Springer, Heidelberg, Switzerland 2015. DOI: 10.1007/978-3-319-15786-3_3

1.5.3 Prizes and Awards

1. Kasim Al-Salim, “Distributed Demand Side Management solution for Cyclic Blackout Scenarios”, Winner of the First Prize in the IEEE UKRI PES Chapter – Best Student Presentation Competition, 8th Nov 2013, Edinburgh, UK
2. ‘Thanks and Appreciation’ Certificate from Dr Hussain Al-Shahristani The Iraqi Minister of Higher Education and Scientific Research, concerning the efforts made throughout this research, its outcome, and important to Iraq, London, UK, 17/1/2015

الملحقية الثقافية العراقية - لندن

شكر وتقدير

السيد قاسم عبدالقادر صالح السالم المحترم

تقديراً لإنجازاتكم العلمية ومشاركتكم في المُؤتمرات العالمية ونَشْركم البحوث في
المجلات الرصينة ورفع اسم العراق في المحافل الدولية، نتقدم اليكم بالشكر والتقدير
متمنين لكم الموفقية في خدمة الوطن العزيز والى مزيد من العطاء.

الاستاذ الدكتور حسين الشهرستاني
وزير التعليم العالي والبحث العلمي

2015/01/17

Chapter Two
Power Shortage Mitigation

2.1 Introduction

The International Atomic Energy Agency (IAEA) highlighted the escalating power shortage problem in its statement that “one in four people still have no electricity” and posed the question “how much will it cost to bring the needed power to more people?” [12].

This chapter begins with an overview of the range of power shortages that plague many countries throughout the world, supported by a classification of the differences between blackouts, power shortages, chronic and cyclic blackouts to prevent any ongoing confusion due to terminology. Power shortage case studies are given with emphasis on the scenario currently prevailing in Iraq. The Iraqi case study is underpinned by a review of the solutions developed to mitigate the impact across the world through both supply and demand side measures. The distinction between ‘demand side mitigation’ and ‘demand side management’, where the latter is part of the former, is highlighted.

2.2 Global Electric Power Status

Electric power is one of the core infrastructures of modern civilisation which has undergone extensive development to offer a wide range of attributes; power is generated from different resources, delivered across short and long distances, transformed to other forms of energy and has the ability to be stored. This flexibility has facilitated penetration into nearly every aspect of modern society which in turn has become strongly dependent on it. The recent proliferation of consumer devices and the growing industrial base across the world has created an ever escalating demand and despite the fact that every country recognises the importance of electric power and indeed each has invested heavily to create its own generation, transmission, and distribution capability, in 2010 more than 1300 million people still remain with no electricity mainly concentrated across Africa and Asia [13]. The huge 'power divide' population is correlative with rising substantial power shortages.

A number of countries are currently plagued by severe power shortages and hindered by crippling load shedding programs e.g. in Pakistan power is shed for 12 hours in urban areas and for 20 hours in rural areas [14]. The situation is even more pronounced in some regions of India in which power is supplied between 2-6 hours per day, usually during the night hours [15]. In Bangladesh, 13 million households have no access to electricity and the rest suffers from frequent outages [16]. Similar power shortages have dominated Iraq since 1996 owing to successive wars [17].

It is estimated that the global electricity demand will increase by nearly 70% by 2035 (compared to 2011), escalating at an average rate of 2.5% annually from ~19000 TWh to 34500 TWh. The increase is attributed to industry and rural electrification, the proliferation of appliances and the expanding built environment [14]. Over the same period, the installed power generation is estimated to increase by the same percentage rising from 5650 GW in 2012 to 9760 GW in 2035, calculated after consideration of an estimated retired power plant capacity equivalent to 1940 GW [14].

Many factors erode the value of increasing installed generation and fuel the gap between power demand and supply. [18] shows that during the period 2000-2008 the factors behind power shortages in Bangladesh, Brazil, China, Dominican Republic, Ethiopia, Europe, Ghana, Kenya, New Zealand, Norway, Pakistan, Rwanda, South Africa, Tanzania, Tokyo, Uganda, USA Pacific coast, and Vietnam were drought, since 16% of the world generation is produced by hydropower and approximately 90% of global power generation is water intensive [13]; heat; failed sector reforms; transmission failure due to a range of reasons; financial liquidity resulting in the inability to buy fuel to power stations; natural disasters such as earthquakes, hurricanes and tsunamis; nuclear power plant safety shut-downs as in the shut-down of other nuclear power plants after the destruction of the Fukushima nuclear facility in Japan; exceptionally cold weather; poor load factor; rapid growth in demand; the inability to maintain water levels in reservoirs; coal shortages; and insufficient investment [19]. It is estimated that the world needs $17 trillion of investment in the power sector over the period between 2013 and 2035, comprising 58% for building new power plants and the remaining 42% for transmission and distribution networks [14].

Other factors such as transmission and distribution losses, power theft, and measurement errors exacerbate the magnitude of the shortage. Globally, in 2012, the length of the transmission and distribution network is >69 million kms; it is estimated to reach 94 million km by 2035. The exceptionally long distribution network losses is equal to ~1000 TWh which is deducted from the total generation; these losses are estimated to reach 3150 TWh in 2035. These kinds of losses are significant, reducing the usable power by ~35%, as was the case in Iraq in 2010 [17].

Power shortages not only affect developing countries but developed geographies also suffer. Neither a country nor a power system is immune to power shortages, the main difference between developed and developing countries is the ability to manage/rectify this damaging scenario.

2.3 Blackouts and Cyclic Blackouts

At the outset, it is worth clarifying the difference between these two key terms since they appear synonymous; they are distinguished by their respective root causes.

The complexity of modern power systems and their extent - in many cases, the network covers a number of neighbouring countries - render such a massive infrastructure vulnerable to many factors that can create a series of cascading events leading to an interruption of the energy supply. The resultant power blackout can last from several hours to several days depending on the severity of the case.

A cascading failure is defined as a sequence of dependent failures of individual components that compromise the power system [20]. Blackouts occur in almost all developing and developed countries with different frequencies, triggered by several factors. Figure 2.1 shows the potential direct and indirect origins of blackouts and outages around the world and although some factors are indirect such as climate changes, they are nevertheless highly impactful. Both power-rich and power-starved systems are prone to blackouts, not related to power shortages in any way; examples of blackouts are given in [21].

‘Cyclic blackouts, although related to blackouts, are different in characteristic, and are effectively rotational load shedding used to distribute available but restricted power among the customer base in an equitable manner resulting in a series of ON/OFF periods repeated daily, referred to as a cyclic blackout. If the power shortage continues for an extended period of time, the cyclic blackout turns into a chronic one.

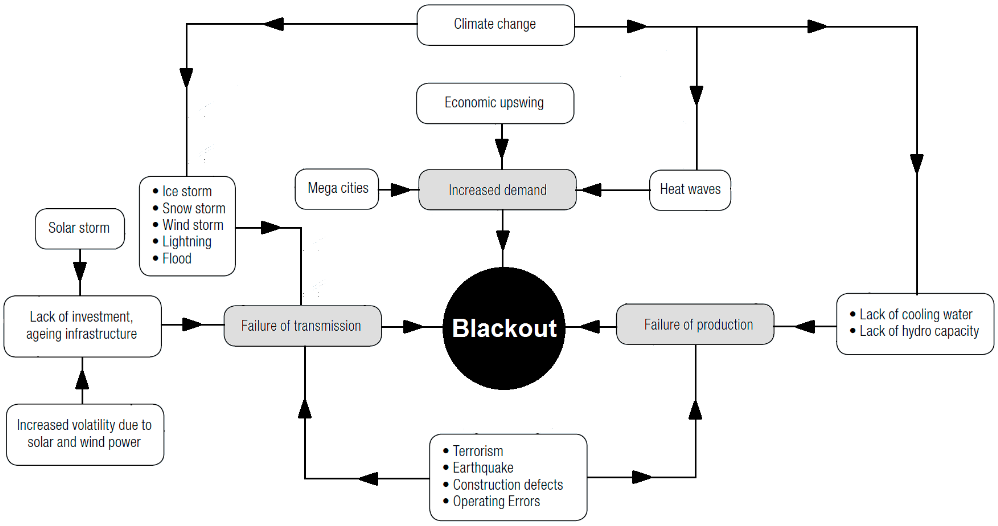

Figure 2.1: The causes of blackouts [22].

In a cyclic blackout, the length of the ON period depends on the severity of the power shortage; in some countries, as in Iraq, typical periods are (3 x 3) hours and (4 x 2) hours but on occasion, during severe shortages periods, this duty cycle can reach (1 x 11) hours. Figure 2.2 shows the difference between power delivery during a blackout (upper graph) and a cyclic blackout (lower graph).

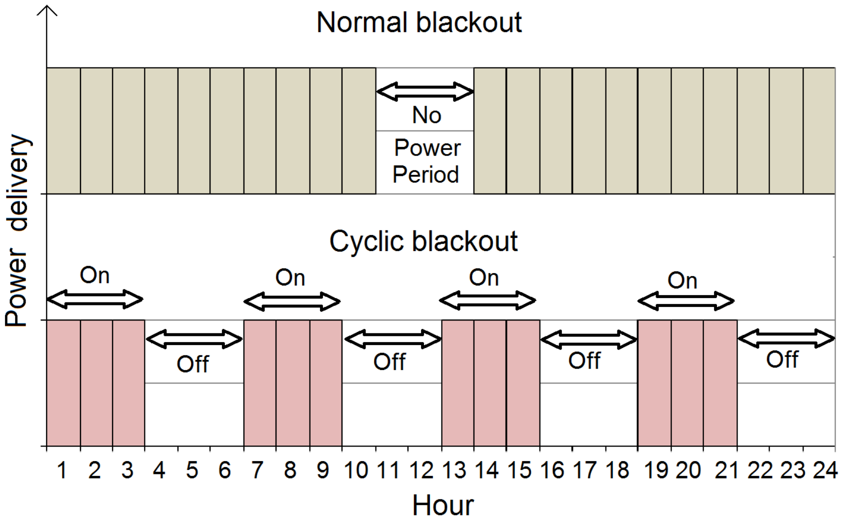

Figure 2.2: The difference between a blackout and a cyclic blackout.

2.4 Power Shortage Taxonomy

Electrical power generation consists of converting one form of energy e.g. chemical, thermal, light and kinetic into electricity. Thus power shortages can be considered as [23]:

- energy-related; the inability to generate electrical power due to drought, insufficient funds to buy fuel, high transmission and distribution losses
- capacity-related; such as insufficient generation, congested transmission and/or distribution or when peak demand exceeds available capacity [18]

An example of the former is Brazilian energy crisis 2001-2002 [24] while an example of the latter is the Pakistani power crisis [25]. Alternatively, electric power shortages can be classified according to their life span to:

- firstly, transient, which can last from hours to days such as the USA-Canada 2003 blackout that induced a seven day cyclic blackout in Canada [26]
- secondly, severe, which lasts from months to few years such as the Japanese

2011 power shortage and the infamous Fukushima nuclear power incident [24]

- and finally, chronic which lasts for many years such as the Iraqi power shortage [17].

Identifying the type of the power shortage and anticipating its duration are crucial factors in managing its consequences e.g. short term power shortages require relatively simple actions such as turning extra lights off and shifting loads while long lasting shortages require more significant interventions such as tariff change and/or rationing of the available supply.

2.5 Power Shortage Case Studies

In order to provide a better insight of the impact of power shortages, four major power shortage events are presented as case studies, in addition to the Iraqi scenario which forms the focus of the solutions developed within the research.

2.5.1 Brazilian Power Shortage (Drought)

Brazil depends heavily on hydropower for provisioning essential segments of its total electrical demand owing to the availability of significant river networks throughout the country. The dependency on relatively low cost resources translates the burden of the investment to the building of hydro-electric generation capability which is labour intensive, slow to completion and sensitive to droughts.

In 2001, ~91% (60 GW) of all Brazilian power generation capacity (66 GW) was provided by hydropower, 6.4% (4200 MW) from thermal and ~3% (1.9 GW) from nuclear; the peak load was ~57 GW. At that same time, a major shortage in rain fall coupled to a delay in the investment in gas-fired generation plants, led to a severe power shortage, a clear example of a shortage where the power generation capability although established, had insufficient head of water to provide the drive [24].

2.5.2 Pakistani Power Crisis (Lack of Investment)

Although Pakistan has nuclear, thermal and hydropower resources, it nevertheless still suffers from severe power shortages that continue to escalate from year to year. In 2007, the power shortage stood at 1920 MW, rising to 4575 MW in 2008 then to 6520 MW in 2012, representing increases of 11%, 24%, and 29% respectively in the total demand [25]. The shortage in power is predicted to double by 2015 [27] despite the fact that 38 % of the population still have no access to power [28].

The sharp increase in demand, neither covered by installing new generation assets nor through deploying a range of Demand Side Management (DSM) measures, has resulted in harsh, repeated power outages manifest as rolling blackouts e.g. Punjab 6, Sindh 3 and Baluchistan 4 times a day despite the fact that the annual per capita consumption in Pakistan is one of the lowest in the world (640 kWh) compared to the USA (13000 kWh) [29]. The forecasted demand will be 20,670 MW, 28,150 MW and 34,980 MW in 2010, 2020, and 2030 respectively which will exacerbate the magnitude and frequency of these rolling blackouts if effective solutions are not implemented.

2.5.3 USA and Canada Blackout (Faults, Accidents, and Human Errors)

The North American power system is highly advanced, its assets worth more than a trillion US dollars, comprising 320 thousand kilometres of transmission lines, supplying 950 GW and including nearly 3,500 utilities serving more than 283 million customers [26].

In 2003, 50 million people in the Northwest and Midwest of the United States and in Ontario, Canada were without power due to a blackout. The blackout started mid-afternoon due to faults, accidents and human errors. Total restoration of the power system was completed a week later. The economic losses of the blackout were severe, for example, Daimler Chrysler scrapped 10,000 vehicles and lost production at 14 plants while at Ford Motors the blackout caused molten steel to solidify inside one of their major furnaces. The blackout also ignited an explosion of a carbon monoxide boiler in an oil facility causing the release of a mixture of hydrocarbons and steam forcing police to evacuate extensive neighbourhoods around it. 237 airports were closed, 1,000 flights cancelled and 1 billion US dollars was lost by New York City business alone [22]. It is estimated that the total USA and Canadian losses amounted to \$4.5 - \$8.2 billion and \$2.3 billion Canadian dollars respectively. The blackout was so severe that the gross domestic product in Canada fell by 0.7% in August. Parts of the Canadian territories experienced limited period cyclic blackouts due to the severe power shortage [26].

2.5.4 Japanese Power Crisis (Natural Disaster)

On 11th March, 2011 an earthquake of magnitude 9.0 resulted in a devastating tsunami that struck the eastern Japanese coastline and resulted in the destruction of 200,000 buildings, the death of 22,000 people and the shutdown of 4 out of 6 nuclear reactors in the Fukushima Daiichi nuclear power station, 3 of which suffered core meltdown [30]. This resultant nuclear catastrophe is considered to be as serious as Chernobyl even though the damaged Fukushima nuclear reactors emitted only 5% - 10% of the amount of radiation emitted by the Chernobyl reactor. ~27 GW was estimated to be out of service [31] owing to Fukushima; in addition the Japanese authorities also shut down other nuclear and thermal power stations resulting in an additional ~52 GW power shortage in the area.

In order to maintain an adequate power supply, the entire affected region was subject to a tight cyclic blackout enhanced in great part by responsible behaviour from consumers. The cyclic blackout was so restrictive that even the traffic lights were turned off. Areas of Tokyo were also subject to different cyclic blackout schedules; for example 17% of shopping stores in Kunitachi suffered one blackout session, 45% suffered two to three sessions, while 32% suffered more than four sessions each day [32]. The total overall losses were estimated to be \$210 billion, the costliest disaster in history [33].

Several immediate measures were taken to mitigate this severe power shortage amongst which were speeding up the maintenance operations of thermal power plants subject to regular scheduled maintenance and/or repair, increasing power purchases from other sources, enhancing the output of hydro-electric power plants and re-commissioning of a 2.27 GW suspended thermal power plant [31]. Other measures were major reductions in consumption for all sectors supported by education campaigns.

2.5.5 Iraq Power Shortages (War)

Iraq represents a unique case due to its post-war political and social status which presents complex challenges [34], amongst those being chronic power shortages. The electricity administration in Iraq has thus far, not succeeded in provisioning sufficient electricity supply which in turn has created a range of cyclic electricity shortage profiles [35]. The main reason for such shortages is the three major wars that Iraq has experienced (the Iraqi-Iranian war 1980 - 1988, first Gulf War 1991, and the second Gulf war 2003). It is estimated that due to US bombardment during the first Gulf War, 75%, (equalling 9300 MW) of the Iraqi installed capacity was crippled leaving only 2300 MW for consumers [36].

In addition, extensive refurbishment across all sectors took place resulting in a rapid increase of demand during the Iraq post war period [3], [37]. The demand is expected to increase further in the near future due to the Iraqi government plan to build two million housing units [38] to cover shortages across Iraq. This massive increase in housing translates into a manifold increase in the number of appliances especially air conditioning, a major segment of domestic demand [17]. Air conditioning demand is huge since the majority of households deploy many ACs owing to hot weather; summer periods are a life threatening hazard on babies, children, elderly and the infirm [39].

Iraq was also subject to a strict commercial embargo for the period between 1990 and 2003. The cumulative effect of those conditions, the lack of spare parts and equipment ageing accelerated the severe degradation of its electric power generation, transmission, and distribution infrastructure. Coupled to those core factors, since 2003, the increase in population and thus the demand for new housing and an increase in the Gross Domestic Product (GDP) have further stimulated the demand for electricity [3].

The Iraqi power infrastructure consists of a mix of hydro, gas and thermal generation distributed across Iraq, a high voltage (400/132 kV) transmission infrastructure connecting the local distribution network, a 33/11 kV distribution network delivering power to customers, and an under development centralized automated monitoring and control system with the necessary communications capabilities to monitor and control the power system (Figure 2.3).

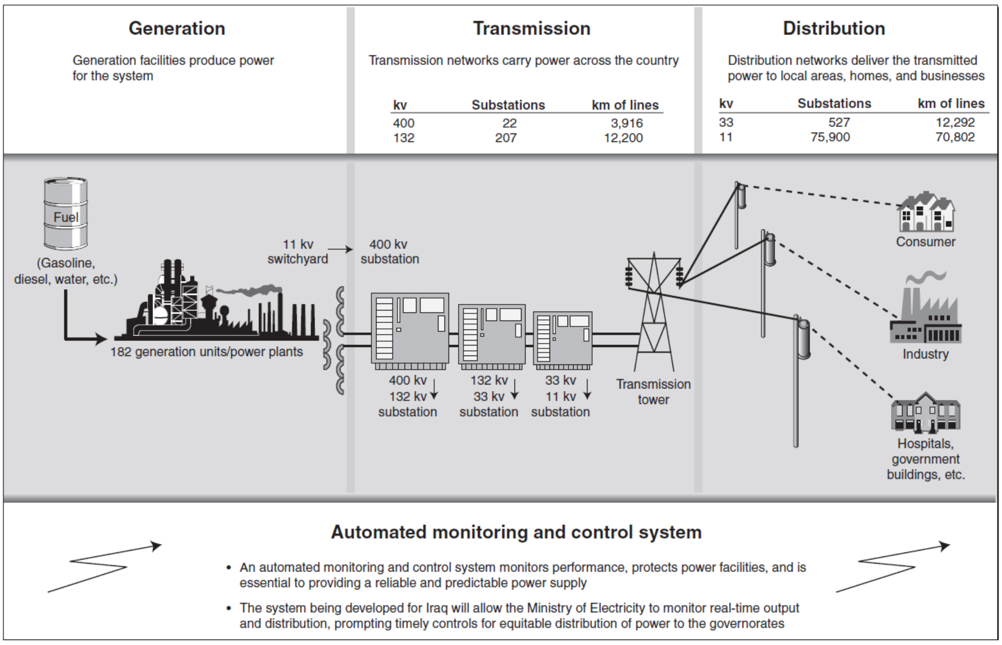

Figure 2.3: The Iraqi power infrastructure [40].

The installed generation in Iraq has a quoted capacity of ∽15 GW of which the maximum deployable capacity is ∽12 GW with only ∽9 GW reaching customers due to several factors contributing to the overall capacity expenditure streams that causes this capacity losses in Iraq. Figure 2.4 shows such streams during 2011 revealing that nearly ∽3 GW are consumed by the Iraqi power system itself, ∽2

GW is lost due to operating thermal plants at high ambient temperature which makes their output declines compared to its normal rates. The situation is exacerbated at peak time load during summer - usually at noon - when the average ambient temperature is around 45°C (and in some area like Basra, it can as high as reach 56°C) and the capacity of the thermal power plants is severely reduced. In addition ∽1 GW are lost due to outages caused by equipment aging, and finally, ∽3 GW due to fuel supply deficiency (especially natural gas) and the unavailability of water due to water shortage in the Tigris and Euphrates rivers and unorganized maintenance scheduling.

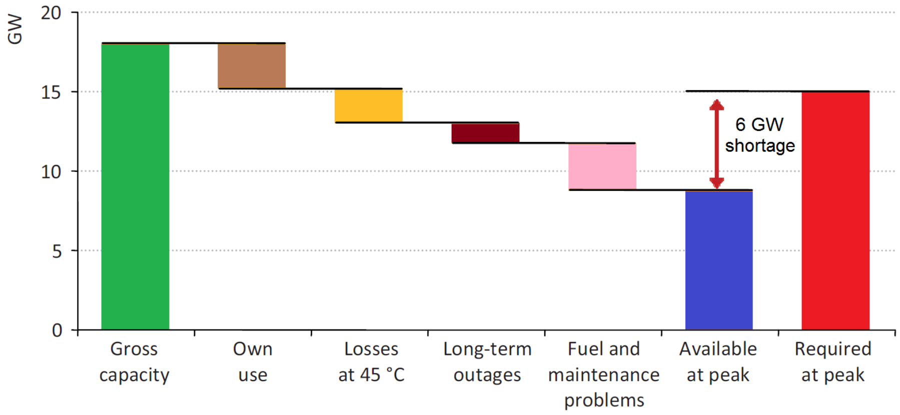

Figure 2.4: difference between gross installed capacity and available peak capacity in Iraq, 2011 [17].

The remaining usable capacity is ∽9 GW which covers ∽60% of Iraqi peak demand, estimated at ∽15 GW. This peak demand is expected to reach 22 GW (assuming a 5% annual increase) and 27 GW (assuming a 7% annual increase) by 2020 [17].

The transmission and distribution losses in Iraq are also extremely high (∽35%), the highest in the region (Saudi Arabia ∽9% and Jordan∽14%, Figure 2.5**)** [4]. These losses are attributed to both technical and non-technical factors; in the former transmission and distribution networks overloading, network aging, poor power factor, high ambient temperature, low efficiency, poor reactive power control and compensation, and unbalanced phase loading; in the latter network destruction during the wars' periods, network sabotage, lack of maintenance, energy theft, power meter tampering, using actual power meter reading and statistical data estimates rather than actual measurements.

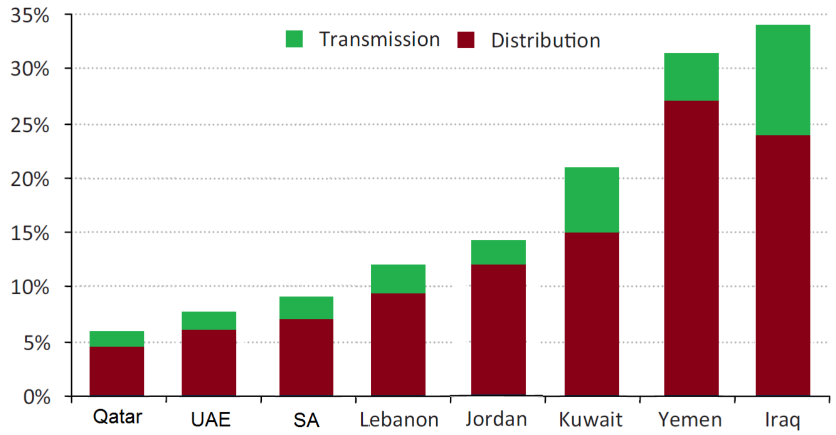

Figure 2.5: The transmission and distribution losses in a number of countries [17].

The scenario has resulted in the provision of a limited daily power supply of nearly eight hours per day [17] distributed as a 2ON×4OFF cyclic blackout duty cycle despite recent measures to supplement the available capacity through electricity imports from Turkey and Iran and the renting of two power ships docking in Basra. These power shortages have had crippling implications on the Iraqi economy in the form of heavy losses estimated to equal $40 billion each year [4].

In an attempt to provision their own, individual power supply needs, 90% of Iraqi households have either acquired private generators or used a shared community capability at the neighbourhood level [41]. Although difficult to estimate accurately, the contribution owing to private/community generation in 2011 was 3 TWh in addition to the grid supply estimated to be 37 TWh [17]. In 2009, nearly 900 MW of private/community generation was provisioned in the central Baghdad area only, a clear confirmation of the degree of dependency and the core role that it plays in covering demand for electricity and to fuel the opportunity for economic impact. The Government supports these private generation facilities through the provision of fuel and covering half of the running cost – during summer - in an attempt to lower the effective cost of generation which is 10 - 15 fold higher than electricity from the grid [17]. The high cost of generation has driven the majority of Iraqis to acquire the bare minimum supply from such generators, sufficient to power the basic set of household appliances i.e. lights, fans, refrigerators, TVs.

Domestic generation is also widely used in Iraq as a standby if all other power sources become unavailable. Domestic generators are not favoured due to their high operational cost (fuel, lubricating oil, maintenance, and repair), noise, smell, emissions, and the risk of fire due to the storage of considerable amount of highly inflammable fuel (most domestic generators work on gasoline) as a consequence of lengthy operation periods owing to repeated and long power outages. The majority of these issues are common to other countries [42] but high operational cost becomes critical only during sustained cyclic blackouts. Figure 2.6 shows household energy supply resources and blackout periods across the regions of Iraq.

The differences in usage profiles are a function of a number of factors such as the availability of fuel, the economy of the region and the severity of the power shortage. With political instability and the concomitant degradation of the power system, a long term, low cost, robust and scalable solution to the ongoing chronic power crisis is not feasible. The stringent restrictions and operating environment indicate the need for a solution that minimises disruption to the legacy system. Nearly 18 years of cyclic blackouts has created opportunities for industrial and commercial organisations in terms of investing in the installation of a substantial amount of standby generation.

In tandem, adding further stimulus to the investment, is the local climate; the extremely hot weather necessitates the widespread deployment of air conditioning which consumes significant power per unit and consequently represents a large element of the overall power consumption of individual dwellings.

Thus the aim of the research is to design and develop a solution capable of mitigating the impact of cyclic blackouts in Iraq. In the remainder of the chapter, a review of blackout mitigation strategies is presented with a view to critically assessing the most appropriate for Iraqi residential sectors. The conclusion is identification of the research gap that the proposed solution addresses.

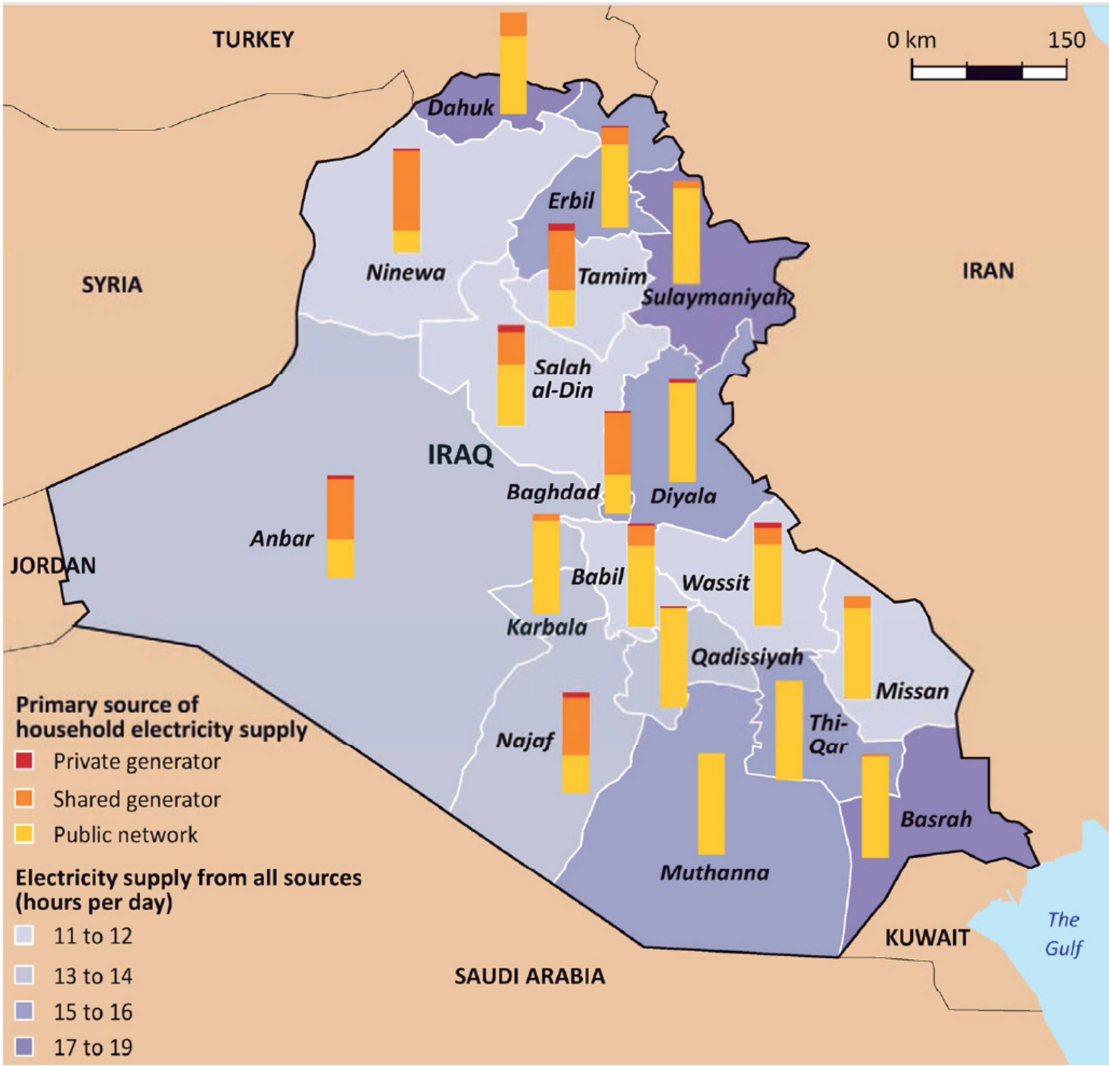

Figure 2.6: Household energy supply sources and blackout periods in Iraq [17].

2.6 Power Shortage Mitigation

A number of mitigation measures have been proposed and evaluated for regions suffering from chronic power shortages around the world. Typically, most measures centre on maintaining the level of power generation higher than peak demand – over-provisioning - in so doing ensuring consistent supply to consumers; this condition can be accomplished either by increasing generation, reducing demand or a combination of both. Deciding which measures to implement is a function of a range of factors such as the severity of the power shortage, the available generation resources, the condition of the power system, customer consumption patterns, time of use, mix of generation, social habits and behaviours, the range of appliances in use per dwelling, weather conditions, financial status, fuel type and cost. The trade-off implies that any mitigation principle has to consider both supply-side and demand-side measures either in isolation or in combination.

2.6.1 Supply-Side Mitigation

In the case of power shortages, mitigation measures focus on generating more power and/or reducing demand. For the supply side, measures can be classified into two main categories based on “conventional generation” and “backup generation”.

2.6.1.1 Conventional Generation

Although investing in additional power generation capacity is an effective solution to anticipated power shortages under relatively stable and predictable conditions, the lengthy implementation cycles of commissioning new power generation plant is not an effective approach to mitigating dynamic and chronic power shortages. Consequently other measures have been developed including systematic and properly scheduled preventive and corrective maintenance protocols, improving the performance of deployed systems through increases in operational efficiency, re-establishing retired and de-rated equipment, reducing transmission losses, reducing measurement errors by installing new metering infrastructure, leasing power generation plants such as power ships and mobile power generation stations, and purchasing power from neighbouring sources [23].

2.6.1.2 Backup Generation (BUGs)

The principles on which the concepts inherent in smart grid operation are founded centre on the intelligent utilisation of all sources of energy generation and storage and their management in order to deliver highly optimised, flexible, services to a mix of customers. A substantial amount of the range of generation assets is in the form of backup units scattered across the customer domain and harnessed in emergencies or as standby power sources.

The main advantage of these assets is their prevalent distribution in cities and rapid responsiveness. The National Energy Technology Laboratory (NETL) estimated that in 2009 the total untapped capacity of BUGs in the USA stood at 170 GW representing 22% of peak load and 36% of average load. In the same year only 47% of the nameplate capacity of the installed conventional generation was utilised continuously, the remainder used for peak coverage [43]. The judicious use and intelligent deployment of these BUGs assets lends itself to managing – smoothing – the 200 peak hours demand per year [44].

Using BUGs to cover peak demand raises the power generation utilisation efficiency and eliminates the need for peaking power plants (‘peakers’), whilst at the same time reducing Green House Gases (GHG) emissions. The Science Applications International Corporation (SAIC) Pollution Reduction Estimator (v1.0) shows that the utilisation of half the available BUGs in peak clipping operations for the 200 hours/year maximum reduces more than 935 thousand tons/year of CO_2, more than 54 thousand of NO_X emissions and more than 33 thousand tons/year of SO_X emissions compared to natural gas peak time generation [43]. The utilisation of BUGs capacity has migrated from the traditional backup role only to grid support generation especially with the penetration of renewable generation increasing throughout the modern power systems [45]. The benefits of BUGS became more evident in the evolution of modern power grids that aim to derive maximum benefit from what to date, have been underutilised generation assets.

During the normal course of operation of a power system there are periods during which demand exceeds forecasted estimates or an unexpected generation shortfall occurs due to unforeseen conditions. The shortfall is dependent on the power system demand profile at the time of the need which varies throughout the year depending on the season, day of the week and weather. At such times, the shortfall that must be managed quickly to cover the ‘generation lag’ for the required duration takes the form of either additional generation or reduced demand [46]. In these cases temporary reserve from different sources under different contracts can be deployed during the shortfall periods. BUGs are one of the candidates in the goal to cover this demand shortfall due to their ready availability and widespread deployment. This type of power security is a well adopted principle in normal power supply planning and is referred to as 'Short Term Operating Reserve (STOR)', defined as a service for the provision of additional active power from generation and/or demand reduction [47]. BUGs are not the only candidate; others, such as PV systems [48] and Electric vehicles [49] have also been researched [50]).

Many utilities and companies are investing in BUGs utilization. Portland General Electric (PGE), a utility company located in Oregon, USA, has realised the potential of BUGs in providing reasonably-priced power for peak time coverage and launched its Dispatchable Standby Generation (DSG) plan in 2000 [51], [52], [53]; Dominion Virginia Power (DVP) offers the Non-Residential Distributed Generation (NRDG) program [54]. On the other hand, companies like PowerSecure Inc., is offering Internet-based power dispatch, monitoring and control of on-site distributed generation (Interactive Distributed Generation (IDG)) used for peak-time and standby power coverage [55]).

The unique dimension of the approach is incentivising customers to participate in peak demand management programs. The extent of the take up of the solution and its coverage area emphasises the importance and potential of utilising distributed generation (DG) for supporting utilities during peak time as well as providing valuable backup power during outages.

These examples show the realization of BUGs potential and their penetration in modern power system. The research aims is to extend this approach by fully utilizing BUGs in order to manage cyclic blackouts.

2.6.2 Demand-Side Mitigation

In essence, demand is the result of the interaction between a number of elements i.e. end users, appliances and electric power usage patterns. Any attempt to control this demand must influence, in some way, one or more of these three demand generating elements (Figure 2.7). Since demand side mitigation targets the management of the overall demand, these measures influence these three.

Thus these measures are mainly classified into three categories; adjustment of electricity prices, increases in the efficiency of appliances, and influencing customer's usage patterns of these appliances; shedding part of the demand is the last resort [18], [23], [56], [57]. Study of the proposed approaches reveals that these measures can be further re-classified into two major principles; adjusting customer behaviour and applying DSM techniques.

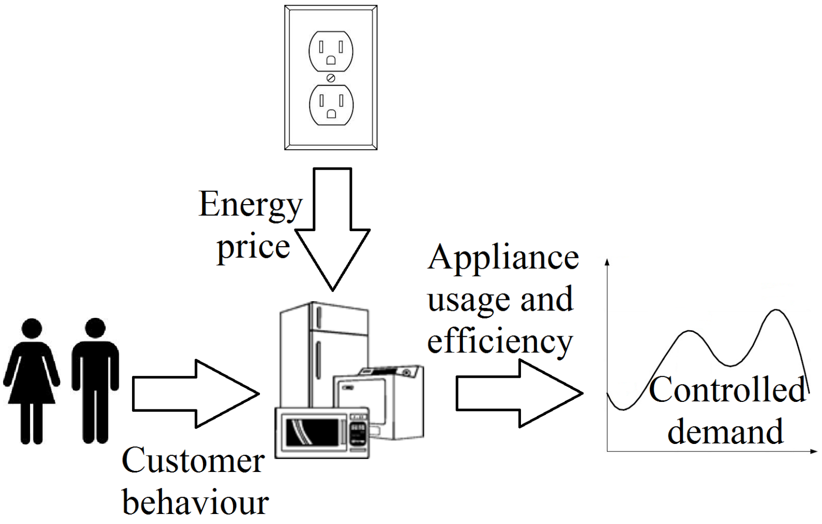

Figure 2.7: The demand side main elements.

Figure 2.8 shows the components that constitute Demand Side Management. Typically, more than one measure is carried out simultaneously to derive maximum impact, a strong function of each application scenario. A mix of DSM implementations worldwide has corroborated the robustness of the approach [23].

2.6.2.1 Changing Consumer Behaviour

Consumer behaviour, preferences and decisions create power demand, define its profile, specify its limits and set its durations. Changing this behaviour can achieve a substantial reduction in demand in a relatively short time [23].

The modulation of power consumption patterns aims at rationing power consumption during peak time and chronic power shortages, various types of contingencies or disasters achieved through incentivising customers to modify their consumption either voluntarily or mandatorily. In the first case, customers are directed and encouraged to ration their consumption through various types of campaigns aimed at informing users about the power shortage, raising awareness of its severity, and suggesting suitable methods of participation to mitigate it. Different energy saving measures are suggested such as re-setting of thermostats, turning off non-essential appliances and various types of lighting, switching from electric to other types of heating (such as gas or kerosene), using appliances more efficiently (such as dish and clothes washers), using natural means instead of forced drying of clothes, reducing ironing time, shifting power usage outside peak time and the selective switching of street lights at night [58].

A well-crafted campaign will educate consumers to change habits, norms, and even investment decisions [59]. Such campaigns are the first stage of a mitigation strategy since they are proven to produce tangible results within a short timescale. Several factors control the effectiveness of such campaigns among them is the choice of communication channel (such as TV channels, poster, meeting) [60].

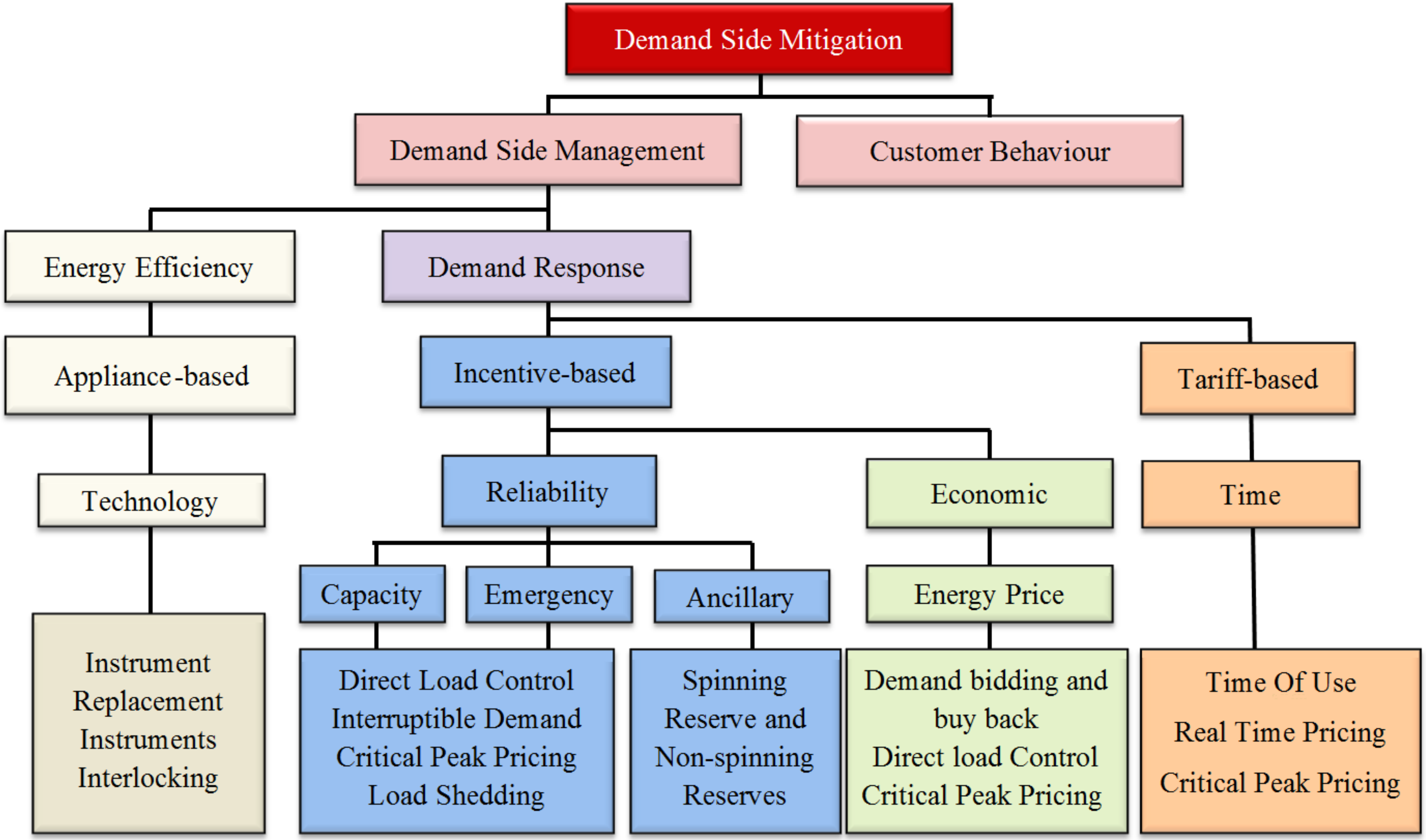

Figure 2.8: Demand Side mitigation principles and processes.

With mandatory rationing, customers are instructed to reduce their demand to a certain limit through compulsory directives and/or regulations and penalties are levied to non-compliant users [23]. An example of voluntary energy rationing is the “10 for 10” campaign in New Zealand during the 2001 drought. The Government requested a voluntary 10% reduction in electricity usage for 10 weeks. An example of a mandatory electricity rationing is the 2001 Brazilian energy conservation campaign, the first of its kind worldwide. The program was launched by an effective nationwide awareness campaign informing consumers on the nature and severity of the power shortage, the rise in the price of electricity for some consumer categories and the detail of the imposition of financial penalties and rewards for non-compliant and compliant customers [61].

2.6.2.2 Demand Side Management

The U.S. National Energy Conservation Policy Act (NECPA) issued the first DSM program in 1978, viewed as the birth of DSM despite the fact that states of California and Wisconsin authorised their utilities to instigate DSM programs in 1975. NECPA authorised utilities to change the level of electric demand and its timing at customer premises, driven by the pressure owing to escalating oil and gas prices [62]. Since that time, DSM has attracted a lot of attention and many countries have deployed programs such as Belgium, Brazil, Costa Rica, Finland, France, India, Japan, Korea, Mexico, Netherlands, New Zealand, Sweden, Switzerland, the United Kingdom, and the United States of America [63], [64], [65], [66].

In general, Demand Side Management despite having many definitions has a well-defined goal. The definition from [67] is “systematic utility and government activities designed to change the amount and/or timing of the customer’s use of electricity”, while others such as [68] defined it as the set of utility programs used to control the amount of electrical energy consumed by customer appliances in order to use the available energy in a more efficient way without the need to install more generation or transmission infrastructure. DSM was defined in [69] as a set of programs which consist of planning, implementing, and monitoring activities executed by utilities designed to encourage consumers to modify their level of energy consumption and patterns of usage, and finally [70] defined it as “a portfolio of measures to improve the energy system at the consumption side ranging from improving energy efficiency through using better materials, through smart energy tariffs with incentives for certain consumption patterns to sophisticated real-time control of distributed energy resources”.

DSM Benefits

The introduction of DSM and the implementation of its principles has offered many benefits and has stimulated the development of approaches to the reduction of demand and peak demand control without incurring heavy investment overheads [64]- [71]:

- controlling customer demand especially at peak hours eliminates the need for building new generation capacity
- increasing the average generation capacity utilisation of power plants, which is around 55%
- reducing demand significantly, and thus energy bills, through various energy efficiency measures such as the replacement of low efficiency with higher efficiency appliances
- eliminating transmission and distribution network overloading
- enabling SDM operations, thus facilitating the integration of intermittent renewables into current power systems and networks without jeopardising the security of the supply.

DSM Challenges

Several factors have hindered the widespread deployment of DSM and a number of major challenges remain [71]:

- the need for an effective Information and Communication Technology (ICT) infrastructure to perform control, metering, and communication since DSM solutions rely on the exchange of key information between the utility and its customers on which decisions are made.

- the lack of understanding of the benefits of DSM among key decision makers such as some Governments, investors and customers due to certain privacy and security concerns.
- DSM solutions are more complex to control than traditional approaches rendering the former more complicated to implement.

2.7 Demand Side Management Categories

DSM offers wide flexibility in providing new solutions to power system challenges. Many DSM classifications have been reported in the literature [70], [72], [73], [74], [75] and they can be categorised as in Figure 2.8.

2.7.1 Energy Efficiency

Continuous modern technology advancements have resulted in more power efficient appliances, lights, and other instruments. The utilisation of such devices offers a substantial reduction in overall demand and can be viewed as an important power shortage mitigation measure and although they take a relatively long time to be implemented, the approach produces consistent demand reductions.

An example of the ease of the approach and regarded as an energy efficiency mitigation measure is the widespread replacement of Compact Fluorescent Lamps (CFL) by Light Emitting Diode (LED) solid state lighting. Many countries have adopted this goal e.g. Argentina, Bolivia, Brazil [76]. To further re-enforce the impact of this relatively straightforward strategy, the Cuban experience is described in more detail due to its notable achievements in Appendix-D.

Here, the research proposes an energy efficiency technique referred to as “HVAC Appliance Interlocking” in which high demand high performance HVAC units are replaced with lower demand lower performance alternatives from the same category for different time durations in an attempt to reduce demand without the need for shedding HVAC loads completely and thus sacrificing customer comfort.

The proposed approach can be extended to include different capacity ACs, air coolers (COs), and Mist Fans (MFs) and represents a compromise between using high load ACs (highly desirable in hot countries) and shedding them completely [11], [8], [77], [78], [79].

2.7.2 Demand Response

In general, Demand Response (DR) refers to the actions taken by customers or operators with the prior permission of customers, to change individual customer power consumption in response to incentives, price, and loss of supply caused by emergencies with or without the participation of grid operators. The definition of DR has remained consistent [80], best encapsulated by the U.S. Department of Energy (DOE) as changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardised [81]. DR is an active demand reduction process which consists of aggregating reactions of one or more customers responding to a personal decision aimed at exploiting an economically beneficial opportunity or in response to an alert from the local utility of an anticipated emergency or capacity shortage.

DR actions are short term demand controls (hours during a day or a year) such as curtailing peak time demand; longer term actions are aimed at moderating customer behaviour. DR is an important measure in modern power systems, controlling residential, industrial, and commercial customers demand at peak hours deriving significant savings. As an example, in the USA it is estimated that shifting 5%-8% of on-peak demand to off-peak periods will result in shaving between 4%-7% of the same peak demand providing customers and businesses with ~$15 Billion of savings each year [75]. Figure 2.9 shows the importance and penetration of DR in modern power systems.

DR events are always initiated with a notification from the utility, market operator or Load Serving Entity (LSE)[2] requesting activation of the activity, followed by a preparation period during which the customer (for most cases) starts to reduce demand within a given period of time, the 'Ramp Period (RP)'. At the end of the RP, the DR activity takes place and continues for the contracted period, the 'Sustained Response Period (SRP)'. At the end the SRP, customer re-establishes the normal daily profile, the 'Recovery Period'.

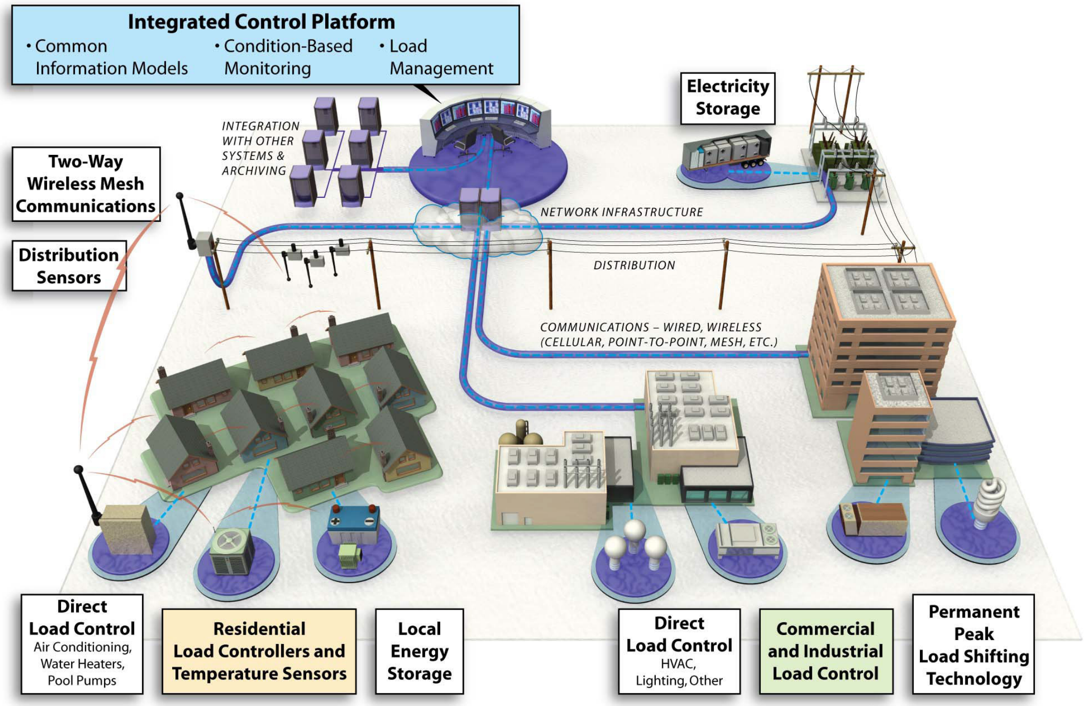

Figure 2.9: The impact of DR in modern power systems [82]

Figure 2.10 shows the time segments of a DR application and its major activities; these periods are implementation dependent and defined explicitly in each contract.

DR programs are agreements between different participants in modern power systems and market, such as: nation-wide regulators and policy makers;

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[2] "Any entity, including a load aggregator or power marketer, that serves end-users within a control area and has been granted the authority or has an obligation pursuant to state or local law, regulation, or franchise to sell electric energy to end-users located within the control area." [75]

aggregators; local agencies such as municipalities; system operators such as utilities and Independent System Operator/Regional Transmission Organization (ISO/RTO) [3]; utility management; DR program administrators; third party program providers; vendors; consultants; customers; and generation, transmission, and distribution planners.

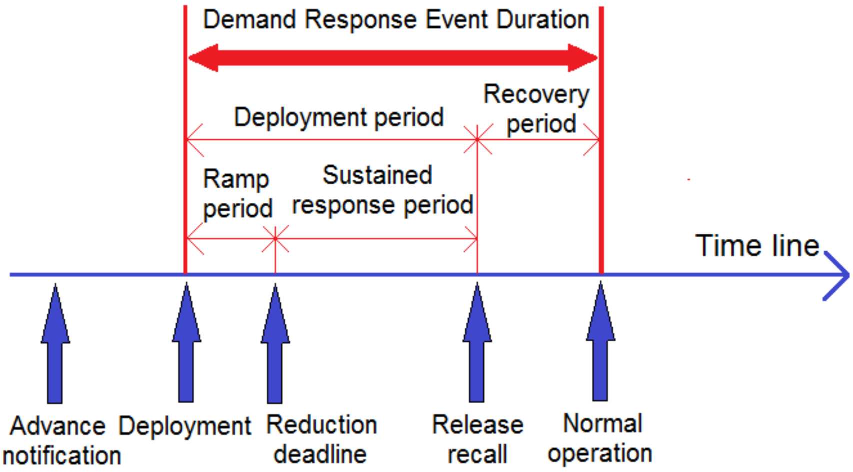

Figure 2.10: DR application time segments [72].

2.8 DR Benefits

DR programs offer several key benefits to power systems and their customers [83], [84]:

1. reduction in demand through a number of measures
2. shifting loads from peak to off-peak time thus reducing the need for peakers
3. reducing GHG emissions
4. reducing the level of investments to expand transmission and distribution networks through a more even distribution of consumption
5. eliminating the need for new investments due to the reduction in current demand obviating the need to build new power plants
6. better power shortage and blackout mitigation management such as

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[3] ISO/RTO is an entity responsible for providing non-discriminatory access to the available transmission network. [256]

dispatched demand during emergencies

7. providing various types of dispatchable and non-dispatchable reserve for the benefit of the grid
8. improved balancing of renewables intermittency to the supply-demand using dispatched loads
9. helping customer to reduce energy costs
10. providing a means for customer to generate revenue from their distributed power generation under DR schemes in partnership with the utilities.

2.9 Demand Response Modes

There are two main DR modes i.e. Incentive-based and Tariff-based; the former comprises reliability (capacity, emergency, and ancillary) programs such as Direct Load Control (DLC), Interruptible/Curtailable Demand, Spinning Reserve (SR), and Non-Spinning Reserve. Incentive-based programs also include economic programs such as Demand Bidding and Buyback. On the other hand, the latter includes mainly Time of Use (ToU), Critical Peak Pricing (CPP) and Real Time Pricing (RTP) programs. Many of these programs are applied as an integral element of other approaches e.g. DLC and CPP. Normally, the extent of the DR applied is a strong function of the scenario being addressed.

2.9.1 Tariff-Based Demand Response

Raising the price of electricity and offering incentives are important drivers for customers to control their demand during critical and pre-critical periods. Doubling the electricity price can produce a 10%-20% reduction in the power demand [85]. Extreme caution should be taken when setting electricity price during power shortages since at such times, power prices can escalate to a level that places an unrealistic burden on low-income groups. To avoid such a damaging scenario, residential areas and other small customers should pay their bill according to a fixed price tariff in tandem with a multi-level tariff in which the electricity price increases as the consumption increases. Changing electricity tariffs is not an easy option since many economic, social, and political obstacles can complicate its implementation. In practice, any new tariff reaches low-demand residential customers at a significant time delay after release. All these factors prevent tariff-based DR from having a rapid impact and it is best viewed as medium term mitigation measure [58]. Tariff-based DR includes mainly four main pricing mechanisms [70]:

2.9.1.1 Time-of-Use Pricing

The Time-of-Use pricing is the predominant type of tariff scheme. In its simplest form, the TOU price is switched between two main tariffs depending on the ToU of electricity (on-peak and off-peak) [86]. In a more elaborate TOU scheme, a third peak shoulder tariff exists. TOU tariffs differ between suppliers depending on their peak demand; some employ a bi-daily or tri-daily tariff, while others consider normal week days and weekends. Some scenarios offer a bi-yearly segmentation scheme in which different halves of the year are subject to a different tariff.

2.9.1.2 Real-Time Pricing

In this pricing scheme the energy price is linked directly to a wholesale power market spot price so that they rise and fall together; several variants of this scheme exist [75].

2.9.1.3 Critical-Peak Pricing

Critical Peak Pricing is not a standalone pricing scheme, but superimposed on other types of tariff such as TOU. The base tariff e.g. TOU is applied throughout the day except for a contracted, pre-determined number of peak days whose exact dates are not set or known when the contract is signed, during which power is sold at RTP rates [87]. Several CPP derivatives are offered in the market [75].

2.9.1.4 Block Tariff

In this tariff, power consumption is divided into ranges and each range has its own tariff depending on the type of customer i.e. residential, commercial, and industrial. Energy price increases as the demand crosses the boundaries of each consumption zone, the higher the demand the higher is the tariff. This type of tariff must be accompanied by a life-line tariff for people in need, providing a minimum supply of electricity to maintain an acceptable living standard [88].

Figure 2.11 illustrates some of the above pricing schemes.

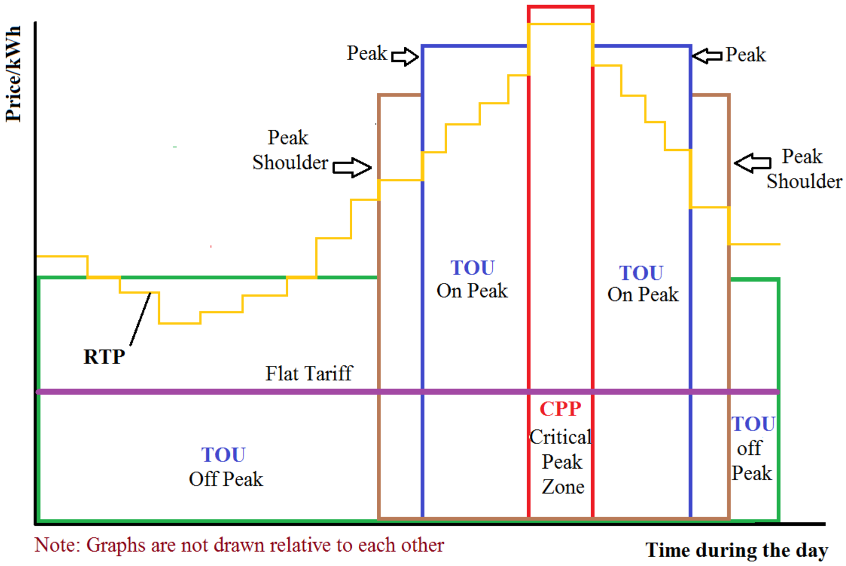

Figure 2.11: An illustration of a number of electricity tariff schemes.

Tariff-based DR programs depend on the response of the customer to a change in price which currently is neither measureable nor predictable; hence these schemes are referred to as ‘non-dispatchable’ whilst incentive-based are ‘dispatchable’ [72], [73], [74]. Tariff-based programs are outside the scope of the research and for further information refer to [89], [90], [91], [92].

2.9.2 Incentive-Based Demand Response

In this class of DR programs, utilities offer incentives to customers to encourage reductions in consumption as an alternative to blocking them from using electric energy freely especially at peak hours or power shortage times. Incentive-based DR mainly includes:

2.9.2.1 Interruptible/Curtailable Tariffs

These programs are offered by utilities to large customers who can shed significant loads, the customer being rewarded with a rate discount or bill credit if they reduce a block of their demand or reduce their demand to a certain threshold within certain period of time (e.g. 30 minutes) during certain times such as during contingencies; if they fail to fulfil these obligations, customers are penalised. Examples of qualified customers are water companies, large sewage plants and chemical factories [93].

2.9.2.2 Demand Bidding/Buyback

In these programs large customers are offered the opportunity to bid for a certain reduction in their demand, for a specified amount of time, and on a certain date in exchange for being paid the price they specify or a market price payment for their supply [75].

2.9.2.3 Emergency Demand Response

In these programs customers are given the opportunity to participate voluntarily in covering power shortage during emergencies by reducing their loads in exchange for pre-specified incentive payments. Customers have the freedom to participate in such load reduction during contingencies without suffering any penalties. An example of such program is the New York Independent System Operator-Emergency DR Program (NYISO-EDRP) [94].

2.9.2.4 Capacity Market Programs

Here customers or any LSE offer pre-defined reductions on their demand or the demand they control in case of contingencies in exchange for guaranteed payments whether their load reduction are activated or not, whilst at the same time accept penalties if they fail to do so. Providers of such programs prefer them due to their guaranteed payments whether their services are needed or not whilst grid operators prefer these programs due to their dependability and fast response [75].

2.9.2.5 Ancillary-Service Market Programs

These are around-the-clock reliability-related services such as regulation services during normal system operation or Spinning and Non-Spinning Reserves during contingencies [95]. In such services, loads are utilised as a form of operating reserves and as relief during peak time power shortages by decreasing their consumption when needed. When a customer commits the utilisation of his load as an operating reserve that can be dispatched on short notice in a dynamic power market, a payment is made governed by the spot market energy price. Loads such as large pumping systems, air conditioning systems, arc furnaces are qualified examples of such dispatchable loads[4]. Different kinds of ancillary programs are available [96]. DR participation in Ancillary Services typically is categorized into two main categories; regulation and reserve [95].

2.9.3 Direct Load Control

Direct Load Control is one of the most mature techniques which has undergone development and enhancement since the 1960s. In such programs a utility or a system operator remotely controls the operation of appliances through turning them ON and OFF or changing their operational settings (such as their thermostat setting) in order to reduce demand during power shortages in exchange for a certain incentive in the form of bill credit or payment. This remote control of high demand appliances is limited to a number of hours each year.

Most DLC programs control ACs and water heaters; each is connected to an individually addressable remotely controlled smart thermostat or multi-relay switch. The latter provides the utility or system operator with the ability to target certain customers and control more than one appliance using the same switch, allowing the capability to fine-tune the control strategy [75]. The overall demand reduction depends on the size of the population of appliances, their usage patterns, and weather at usage day.

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[4] **Ancillary services:** Services that ensure reliability and support of the transmission of electricity from generation sites to customer loads. Such services may include load regulation, spinning reserve, non-spinning reserve, replacement reserve, and voltage support. [251], [255]

2.9.3.1 DLC Challenges

There are certain challenges and requirements that face any DLC measure [97]:

- an effective DLC measure should be fully responsive since the generation capability that the DLC measure is intended to substitute, is fully responsive
- should also not disturb customer's normal activities; otherwise customer collaboration is either compromised or becomes more costly
- must not create a new peak elsewhere in the system during the day due to load forecasting errors and uncertainties [10]

2.9.3.2 DLC Benefits

DLC has a number of advantages [97] over typical generation:

- loads respond to DLC almost at real time, more rapidly than generation
- the availability of widespread communication and advanced metering infrastructures in addition to the even spatial distribution of loads reduces the requirements for utilizing these loads in SDM operations to just develop the right strategies and algorithms
- failure of some loads amongst a large population of controllable smaller loads has less impact on the supply-demand balance than the failure of a significant generator
- the distributed nature of loads matches the distributed nature of renewables and provides local SDM through the active management of the intermittent characteristic of the generation
- the distributed nature of loads makes their utilization easier in local DLC-based power outage mitigation operations due to their proximity to faults
- using loads for DR purposes reduces overall GHG emissions.

2.10 Conclusions

Power shortages as well as differences between normal and cyclic blackouts have been introduced supported by a number of sample case studies, the most notable being the prevailing Iraqi scenario. Evidence indicates that most, if not all, countries are not immune to losing the supply of power.

A spectrum of reported power shortage mitigation techniques has been reviewed forming the backdrop to the development of an effective power shortage mitigation technique suitable for residential areas, specifically in hot geographies.

The goal of this research is to propose a cyclic blackout mitigation scheme capable of providing sufficient power to sustain basic household appliances and at the same time provide minimum air conditioning coverage during the cyclic blackout power OFF periods throughout the day without installing new generation assets. This implies no reliance on the grid supply. Several main challenges can be identified:

- provisioning of the needed power
- operating the best possible air conditioning/cooling at all available power levels
- distributing their usage period fairly
- no reliance on the grid power and schedules

Existing power shortage mitigation techniques, their attributes, and advantages and disadvantages are mapped in Table 2.1. From this table it can be seen that from the supply side, investing in new power stations is inevitable, yet insufficient in the short term in respect of managing severe power shortage owing to ever escalating demand and the slow building pace of conventional generation plants. However, substantial BUGs capacity is already available - one, or even in some cases more than one in each company, facility, house, public building – and since the majority of them are underutilized, represent a promising asset.

On the other hand, from the demand side, several proven techniques are already in deployment globally, among them is addressing the customer through awareness campaigns and incentives in an attempt to change his usage patterns of appliances. In addition to that, DSM has a rich toolbox of measures that are globally accepted and field proven techniques. Increasing the energy efficiency of used appliances is one of these measures and it is adopted in this research by dynamic energy efficiency replacement of HVAC appliance, not always possible without compromising the customer’s level of comfort e.g. full replacement of ACs with COs.

Furthermore, DR is the other main category of power shortage mitigation techniques, but most of its techniques are inapplicable to the Iraqi case due to several reasons. Tariff-based measures are not effective since the main load in residential areas during summer is air conditioning which is mostly needed during peak periods and there is a necessity to operate the ACs despite cost due to hot weather. CPP, RTP and incentive-based techniques suffer from their need for a power market which is not adopted in Iraq.

Considering all these factors, the proposed solution is based on:

- securing the needed power from existing standby generation within and around the targeted residential areas; no new generation assets are installed.
- since HVAC appliances are the main contributors to the majority of the residential demand they are targeted and controlled using DLC.
- Powering all basic household appliances from the secured power.
- using the remaining of the secured power as the main factor in choosing the best combination of different demand and different performance HVAC appliances to operate in the targeted residential area; this implies using dynamic replacement of interlocked HVAC appliances
- enhanced smart meters are needed to monitor the consumption of each residential entity during the validity period of each secured snooped power level.

In the next chapter, a more detailed examination of the current trends in managing the demand through DLC is given and major projects in this field are examined in addition to mapping the supporting techniques that makes the proposed solution more effective such as agent recruitment.

Table 2.1: Power shortage mitigation schemes.

Power shortage mitigation Measure	Response	measurable	predictable	in Iraq?	Used now	Selected	Pros and Cons
Supply-side mitigation							
Conventional gen.	Long	Yes	Yes	Yes	Yes	No	Slow to build, very expensive, fast response, and added capacity is diminishing by escalating demand
Standby gen.	Fast	Yes	Yes	Yes	Yes	Yes	Fast to add new ones, majority already there, affordable, fast response, near customer premises, new ones can be added as demand grows
Demand Side Mitigation							
Change Behaviour	Fast	No	No	Yes	No	Yes	Needs customer awareness and cooperation, fast response time, neither predictable nor measureable
DSM							
Energy efficiency	Med	Yes	Yes	Yes	Part	Yes	Effectiveness, cost, and response time depends on the targeted appliance
Demand Response							
Tariff-based							
TOU	Med	No	No	No	No	No	Not effective due to cheap power prices in Iraq. Peak time price is applicable at the hottest period of the day when the main load is air conditioning.
CPP	Med	No	No	No	No	No	Same as TOU and it needs power market not available in Iraq
RTP	Med	No	No	No	No	No	Same as TOU and it needs power market not available in Iraq
Block pricing	Med	No	No	Yes	Yes	No	Not effective due to cheap power prices in Iraq and needs continuous consumption monitoring whose equipment are not available at Iraqi houses.
Incentive-based							
Demand buyback	Fast	Yes	Yes	No	No	No	Needs power market not available in Iraq
Interruptible loads	Fast	Yes	Yes	No	No	No	Needs power market not available in Iraq
DLC	Fast	Yes	Yes	No	No	Yes	Established technology, effective, has fast response, and provides direct control over customer appliances

Chapter Three
Background

3.1 Preface

Electric power management has attracted a lot of attention due to its importance in modern societies and the vast number of different aspects and factors affecting it. In this chapter, a review of major research in the field of DLC is presented. The chapter concludes with a definition of the research gap, the foundation for the proposed solution.

3.2 Residential Energy Usage Spectrum

Domestic demand is created through the interaction between users and their appliances within home environments. Researchers have identified several factors that impact this demand [98], [99]:

- Residential building structures such as insulation type, window specification and passive solar design. [100] state that in many countries as a consequence of the quest for modernisation, people have replaced environmentally friendly, naturally insulated houses with houses made of concrete and steel requiring significantly more energy.
- HVAC specification, type, ducting, and usage patterns. It is estimated that the world consumes 1 TWh of electricity per year just to provision air conditioning demand - more than double the overall African demand - and that demand will increase tenfold by 2050 [101].
- Water heating and cooking specification, efficiency, insulation, type of energy and storage. In oil producing countries like Iraq, natural gas is used for cooking and space heating since its low price makes it preferable to

electricity. This in turn restricts the number of microwave ovens, electric cookers and electric kettles deployed, further accentuating the power consumed by air conditioning demand

- Lighting type, specification, efficiency, number, location and distribution
- Various appliance specifications, efficiency, location, number, usage pattern. In post war Iraq, massive rebuilding programmes took place across all sectors [3] resulting in a rapid increase of demand [37]. The demand is expected to increase further in the near future owing to the Iraqi Ministry of Planning [38] development plan to meet an estimated 2 million shortage in housing units. This massive increase in the population of houses translates into a manifold increase in the amount of appliances especially air conditioning [17], since the majority of households deploy many ACs. This trend is not specific to Iraq, other hot countries show the same pattern e.g. in Saudi Arabia the average number of ACs in each house is 5 with a total of 13,315,000 window type ACs, and air conditioning demand contributes to 61% of the peak load [102].
- Facilities such as swimming pools which are not the norm and considered as a lavish luxury.

3.3 Load Control of Air Conditioning Appliances

Air conditioning demand is a significant contributor to the overall demand in residential buildings [10], [103], [104] and is dependent on various spatial and temporal variables. Researchers estimate this demand to be more than 50% of the overall demand [11], [105], [106], [107], reaching higher percentages[5] in countries like Iraq due to extremes in hot weather [108], concrete-based housing, and natural gas based cooking and space heating[6]. AC demand follows the outdoor

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[5] It is estimated that air conditioning load in typical households in Basra, Iraq reaches more than 85% depending on a calculation of the residential power consumption in Basra, Iraq based on a survey conducted for the purposes of this research.

[6] Surveys have shown the dependency of Iraqi households on natural gas in cooking and heating results in making air conditioning the main contributor to the overall demand.

temperature; a 1% increase in the outside temperature causes a 0.6% increase in the power consumption of residential customers [109], motivating the use of DLC with AC loads for peak reduction [110], [111]. DLC plays an important role in DR due to its fast response and predictable nature [112]. When applying DLC to air conditioning loads, several constraints must be taken into consideration such as weather, load payback and customer preferences [103], reflecting the comfort level which is a key factor in the success of any load management measure.

There are two ways to control the load of a typical residential AC; resetting its thermostat to a higher temperature setting or operating it for some time during the hour and turned OFF in the remaining period [113]. In moderate weather conditions, resetting an AC thermostat to a higher temperature or turning it ON and OFF does not have an instantaneous impact on room temperature due to the 'coolness' stored in the environment and does not have a noticeable effect on its occupants since individuals have a comfort range of temperature and humidity. This comfort range has stimulated solutions to AC demand reduction. Unfortunately, this approach is not as effective in extremely hot countries with poorly insulated housing as is the case in Iraq where ACs operate almost continuously.

The control of a large number of air conditioning appliances for demand reduction implies modifying their operation in an effective manner at minimum compromise to the customer level of comfort. Six main strategies are used to reduce the AC load:

- **adjusting AC thermostats**: the AC thermostat is readjusted to a higher temperature whenever a reduction in the demand is required, including full set-point and 'near-end' set point control.
- **delaying the compressor starting time**: by adding a compressor time delay relay and changing its setting to disaggregate demand
- **control of a multi kW fan speed**: the fan speed of large ACs is slowed to reduce demand.
- **use of thermal storage**: large ACs (chillers) with thermal storage facilities are

used to store the ‘coolness’ during off-peak hours

- **shedding of AC loads**: a selected population of ACs is turned OFF for a certain period of time and this action is repeated periodically amongst all ACs
- **HVAC interlocking**: different demand different performance HVAC appliances are interlocked together and operated one at a time according to the available power, usually ACs are interlocked with COs.

All solutions should not compromise the customer’s level of comfort unless it is inevitable, as in the case of AC load shedding.

3.3.1 Thermostat Adjustment

[114] address the power shortage problem and at the same time prevent any LV distribution networks links exceeding their maximum through reducing the residential AC demand while maintaining all the remaining demand. The solution target a smart grid based environment in which the power company monitors the thermostat setting, inside and outside temperature, and all appliances power consumption including the ACs. It also has the ability to control the thermostat setting for the AC remotely. The fairness criterion is dependent on two factors; the lowest temperature that a household can have and the fraction of cooling that can be given to that household. Two AC power distribution strategies are implemented; min-max and proportional fairness. In the former, a certain thermostat temperature is selected and assigned to all customers requesting lower or equal temperatures in steps while customers requesting higher settings are allocated the request. In proportional fairness, the utility assigns a fraction of the requested thermostat temperature of each customer. The problem with this technique is that at the outset, and despite the temperature set in each thermostat, all ACs must be turned on and all are operational thus a demand peak is generated. The other aspect is that in hot geographies ACs operate for extended periods just to reach a certain temperature.

[107] explore the potential of controlling a big population of ACs through the thermostat set point to achieve a significant demand reduction during peak times.

After a data-gathering phase using various sources and means (audits, surveys, and meter measurements), a hypothetical 900 house community was simulated, based on the data estimated from a pool of 60 physical houses, to test a number of demand management strategies and the impact of power tariff variation. The load model was produced with several assumptions; home occupancy (50% of houses are occupied and 50% are not during certain hours of the day), base load amount (setting the base load for part of houses and assuming it to be the same for the rest of them), changes in energy price do not induce any behavioural changes but changes in thermostat set-point do, and occupants can override their AC thermostat set-point governed by the controller. The research is focussed on minimising peak demand, taking the thermostat set-point and AC demand as control variables and outdoor dry bulb temperature and electricity prices as disturbance variables.

Four AC thermostat set point change strategies were investigated in addition to a base case used for comparison; Minimum cost using wholesale day-ahead market prices, Minimum peak using centralized control, Minimum peak using decentralized control, and Minimum peak using decentralized control with randomly assigned customers penalties that vary across homes and times. All these control strategies were successful in shaving the peak by (4.8%, 8.8%, 5.7%, and 7.7% respectively) but at the cost of increasing the overall power consumption outside peak zone (10.1%, 13.3%, 13.8, and 11.5%). One of the drawbacks of this approach is it needs to keep ACs operational at higher thermostat setting (27.78°C) when the house is unoccupied.

[115] highlight that reducing air conditioning demand through load shedding of air conditioning appliances or changing the thermostat set point often cause degradation in the customer comfort level and a payback caused by the "cold load pickup" [7] phenomenon. A new way to achieve demand reduction is proposed

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[7] Cold Load Pickup is the phenomenon that occurs when power is fed to a group of loads after an outage resulting in an increase demand of those loads above their normal pre-outage levels due to

through changing the setting of the air conditioning appliances thermostats near their end-of-ON-cycle period. The technique depends on the fact that the indoor temperature near the end of the thermostat setting does not differ greatly from the thermostat set-point. This small difference is not discernible by a human being and does not affect his level of comfort. The technique harnesses the thermal mass of the room and its behaviour as a storage device that keeps its coolness for an extended period, similar to using a battery for storing energy at off-peak times and releasing it at peak times. One key feature of the technique is that only part of the AC population is affected by (ACs near the end of their ON cycle) leaving the remainder operating normally, reducing the effect of the cold load pickup. The technique is used for matching the demand of 60,000 ACs with an intermittent supply from a wind farm. The technique is an effective approach in moderate weather environments but is less effective in hot areas because the AC is operational for prolonged time periods in order to achieve the desired set point, i.e. the ON period is much longer than in moderate temperatures, which renders the effect of 'near the end of the ON period' technique less effective. The technique loses its effectiveness when applied to a limited population of ACs as in the case of a typical residential quarter (~500 houses[8]) compared to the 60,000 houses used in this research.

3.3.2 Controlling the Compressor Time Delay

Another way used to reduce the total HVAC demand is through disaggregating HVAC individual demand [112] implemented by inserting a compressor time delay between successive OFF-ON states. In addition, a (+/-) probabilistic control signal is used to order HVAC appliances to either go ON or OFF, appliances that are turned

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inrush current and the loss of diversity leading to the pickup of more connected loads such as cyclic loads based on temperature or pressure. Typically, such loads reach a level of diversity once they are powered for a period of time but after an interruption of supply the diversity is lost and the majority, if not all, will be connected, drawing power for a period of time following the re-energization of the circuit. The current flow to the circuit may be significantly greater than the normal level.

[8] This is the size of Kafaat residential quarter in Basra estimated during the field survey conducted at the beginning of this research.

OFF will be turned on again after the defined delay time. The approach has provided a ~70% total demand reduction of a large population of HVACs a (nearly 2.5 MW regulation capacity of a total of 3.5 MW total demand).

3.3.3 Controlling Fan Speed

Controlling multi-kilowatt fan speed – which results in lower power consumption - in a group of large central air conditioning systems is another approach used to reduce AC demand. [116] use DR to provide ancillary services to the grid; the speed of AC fans in large buildings (whose demand is in the range of 10's kW each) is controlled to provide frequency control services to the grid. Two features are used, the first being the fast response of AC fans leaving aside chillers and cooling coils due to their slow response times and the second is the thermal storage of the building which mitigates the effect of reducing the speed of fans on the overall customer level of comfort. Scaling of results to the USA indicates the approach alone can provide 70% of the total demand needed for the regulation capacity, equal to 6.6 GW.

3.3.4 Using Thermal Storage

Thermal storage is a well-known technology in which an isolated storage tank is used to store chilled water or ice produced by a refrigeration system during off-peak hours and used during peak hours. This technology is most relevant for office buildings and large complexes where thermal storage systems can be integrated as part of the air conditioning system and due to their limited occupancy hours [117]. [118] give examples of some big buildings in Saudi Arabia and the size of their thermal storage systems which ranges from 14 MWh to 100 MWh, both using chilled water.

[103] develop a control algorithm (g-DLC) running on a thermal comfort controller for managing the speed of room fans of a chiller-based centralized air conditioning

systems with pre-stored chilled-water storage capability through a Least Enthalpy[9] Estimation based fuzzy logic, on a one per fan basis. The chiller's compressor is under the control of a load management program responsible for turning them ON and OFF depending on the temperature of the circulating chilled water. The thermal comfort controller varies the room fan speed in an attempt to keep the circulating water as chilled as possible for as long as possible maintaining customer comfort within the accepted limits, a function of outside and internal temperatures and the inside humidity. The approach is claimed to be energy efficient since it prevents the transient payback phenomenon and increases AC load shedding time but at the same time maintains an acceptable level of thermal comfort by minimising the effect of outdoor temperature. The size of the stored chilled water reservoir limits the effectiveness of such controllers.

3.3.5 Air Conditioning Load Shedding

Shedding air conditioning load is a measure considered to be the last resort in case of power shortages. In this approach, part of the AC population is turned OFF depending on the required reduction in the peak demand, for a certain amount of time using DLC. Some of the AC load shedding is contracted in exchange of incentives whilst others are enforced especially in the cases of severe power shortages

[11] propose using controlled AC load shedding to shave the demand peak[10] as a consequence of the strict measures taken by the Israeli Electric Company (IEC) and enforced on Palestinian territories. That user community is considered to be the least priority customers and the target is to limit their electric power share during the hot season which is 3 MW higher than the peak limit set by IEC resulting in cyclic blackouts during that period. For this purpose, a system consisting of a microcontroller-based local controller is located in each dwelling, connected via an

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[9] Enthalpy (H) is the amount of heat content (E) used or released in a system at constant pressure ($H = E + PV$), where P is the pressure and V is the volume.

[10] Identified in this research as West bank Air Conditioning Load Shedding System (WACLSS)

Internet connection to a central controller who monitors the total load and executes AC load shedding for 5-10 mins periods on 10 customer groups, each one consisting of 200 customers with an average AC load of 1.5 kW per customer. The local controller is connected, in addition to the Internet, to the residential digital smart meter and to the ACs to be controlled.

The main advantage of this system is its low implementation cost, short AC shedding periods, scalability, and ability to shed ACs only while leaving the rest of the appliances operational. The proposed system has several disadvantages: it depends on Tulkarim city moderate weather, it can only control only one AC in each house, and if the power supply level is low throughout the day, then the size of the shed AC population will be large.

[119] propose controlling a population of ACs through voluntary participation in an incentive-based DR program across large apartment complexes using a service waiting queue of AC usage rights requests. The proposed system consists of a central and a group of local controllers, one for each AC. All controllers can be equipped with knowledge-bases and inference engines. The proposed technique is based on finding the maximum number of ACs that can be operated with a certain amount of power, then a similar number of tokens are issued (which is less than the total number of ACs), these tokens representing AC usage rights distributed among all customers based on a 'first-in-first served' basis. The local controller of any customer who wants to operate his AC, issues a request for AC usage right for a certain amount of time from the central controller who, if the request is granted, issue a 'usage right token'. The number of issued token depends on the amount of available power. When the current token expires, its owner must request a new token.

3.3.6 Air Conditioning Interlocking

In this type of air conditioning demand management two or more, same or different type HVAC appliances with different power consumption and performance levels such as ACs, COs, and MFs are 'interlocked' together, so that only one of them is powered depending on the amount of available power. The interlocked appliances can include various sizes of each type depending on their deployment. This kind of demand reduction through HVAC control is proposed in this research.

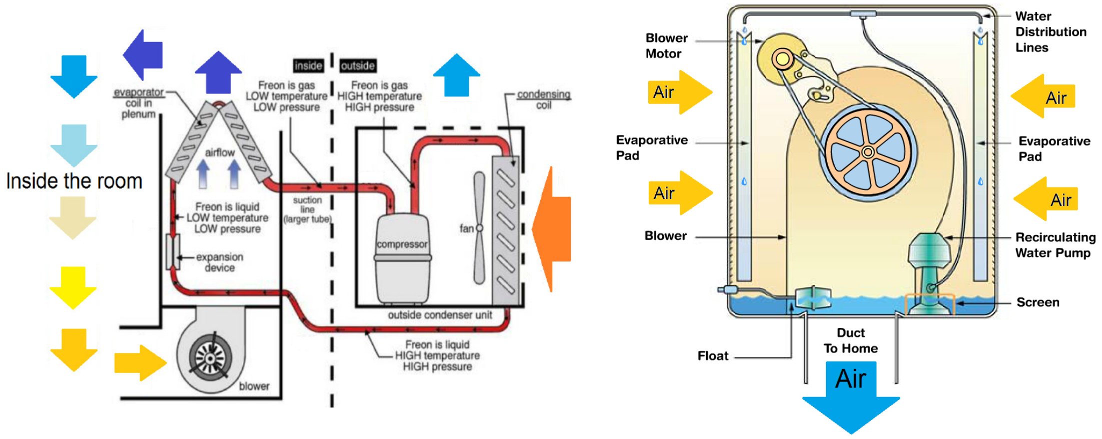
3.4 Air Conditioning Counterparts

The development of air conditioning system has taken two main routes: refrigerant gas based and water evaporation based. In the former an industrial gas is used to absorb heat from one side (inside the room) of the AC and release it into the other side (outside the room) resulting in cooling the air; in the latter, the air is cooled by water evaporation over a wet surface.

3.4.1 Evaporative Air Coolers

Evaporative air coolers, known also as 'swamp coolers', 'desert coolers', or just 'air coolers', are appliances used widely in hot and dry weather geographies such as China [120], [121], Brazil [122], the Indian subcontinent, northern Mexico, and Eastern Africa [123]. They are one type of a family of water-based cooling devices such as misting or drip systems and fogging systems [124], [125] with several applications such as indoor/outdoor cooling, humidification, greenhouse propagation, and dust/odor control. There are three main types of evaporative air coolers [120], [121], direct, Indirect, and desiccant. In the first, air is forced to pass through a wet cooling pad. In the second, two completely separated chambers represent two cooling stages so that the supplied air is kept at normal humidity [126], [127]. In the first stage, the air is cooled as in the direct manner and then it is used to cool another air stream separated by a barrier. The main purpose of this operation is to reduce the amount of humidity in the air stream entering the serviced area. Finally, in the third one, used in humid weather geographies, a desiccator is used to dehumidify the air before being cooled directly or indirectly [128].

CO can provide cooling and ventilation at low energy consumption using water as the working fluid and avoiding the use of Chlorofluorocarbons (CFCs) as in the case of ACs. The air is cooled by the amount of used water and its distribution over the cooling pad plays an important role in specifying the efficiency [129]. COs also provide a reduction in CO_2 emissions owing to the energy efficiency of the technology, and the potential for managing peak electricity demand during extreme hot periods [124]. Residential COs are normally the direct type. Figure 3.1 shows the working principle of a typical residential direct CO compared to a split unit AC.



(a) (b)

Figure 3.1: The working principles of (a) ACs [130] and (b) COs [131]

COs have two cooling effects; the first from cooling the air through the evaporation of water, the second due to the large air flow produced, one of its distinguishing features, which typically ranges from 2500 to 30,000 cubic foot/minute [132]. COs have a number of advantages such as less power consumption than a typical AC. It is worth mentioning that CO cooling is governed by the amount of air pumped in the space to be cooled, measured typically by cubic foot/min (cfm). According to the California Consumer Energy Center[11], a 100 m^2 house needs around 6,000 cfm CO to cool it, which a single CO, such as Breezair EXV-155[12] (refer to Appendix-F for its data sheet), can supply it. This CO has the ability to supply 5,500 cfm of cool air

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[11] From: http://www.consumerenergycenter.org/residential/heating_cooling/evaporative.html accesses on 12/9/2015.

[12] From: http://www.breezair.com/us/help-me-choose/model-specifications

by consuming as low as 500 W for its fan motor and 30 W for its water pump[13]. In Iraq, 4 ACs, each consuming 3,600 W giving a total of 14,400 W, is needed to cool a 100 m^2 house typically having four rooms, and although ACs can lower the air temperature to a lower degree than COs, the latter is nevertheless capable of providing a good level of comfort to customers.

In addition to that, COs are less costly than an AC, do not rely on CFC gases, reduction in CO_2 emissions, improvement in the quality of air inside the house, air change removing odours and pollution, able to cool a full house much faster than an AC, easy to use with direct digital control, and is simple to install and maintain [123]. The main disadvantage is that since its efficiency depends on the dryness of air, its performance degrades in highly humid environments.

3.4.2 Air Coolers and Renewables

COs are the perfect companion to domestic PV systems forming what is known as the solar CO [133]. Such appliances are powered even with the smallest domestic PV system. Systems have shown outstanding performance compared to ACs for example, sufficient to cool a 3,000 ft2 building consuming only 0.6 kW of PV power (compared to a typical AC which consumes between 6-7 kW of grid power) generated by four 200 W solar panels [134] (Figure 3.2).

Figure 3.2: A solar powered CO with 4 panels [134].

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[13] The Breezair EXV-155 consumes 290 W more for operating highly advanced control circuits which is not available in its counterparts, from other brands, which are available in Iraq.

The versatility of COs gates a spectrum of deployment options throughout the world e.g. cooling data centres [135] (Figure 3.3).

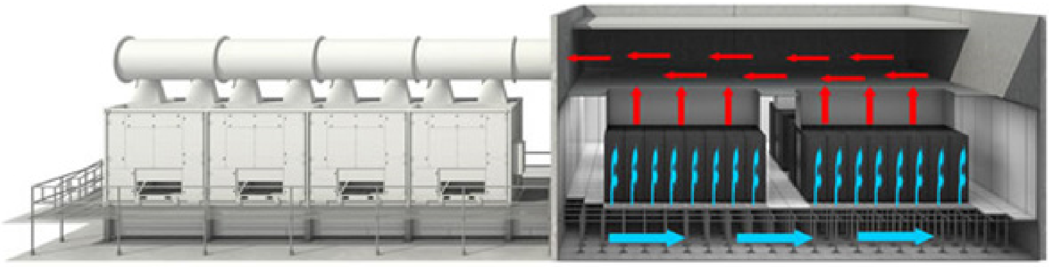

Figure 3.3: An indirect evaporative cooling system for data centres [135].

3.4.3 Mist Fans and Sprayers

Misting technologies have been proven to reduce surface temperature, air-conditioning usage time, and improve air-conditioning efficiency with projected savings in the energy consumption for cooling by over 80% [136]. An MF is a CO derivative operating using the same principle, in which a stream of water is sprayed as a cloud of micro water droplets (as in mist sprayers) or in front of a fan. The air flowing throughout the mist cloud loses heat due to water evaporation, cooling the surrounding area (Figure 3.4). MFs offer several advantages such as very low power consumption, ease of maintenance, low cost, small size and low weight. Different sizes of MFs and mist sprayers are available and are widely used around the world such as Japan [137], Saudi Arabia[14], and Iraq[15] amongst many others. One of the factors identifying the efficiency of an MF is the size of the sprayed water droplets which directly affect water consumption, the air humidity, and resultant level of comfort [138]

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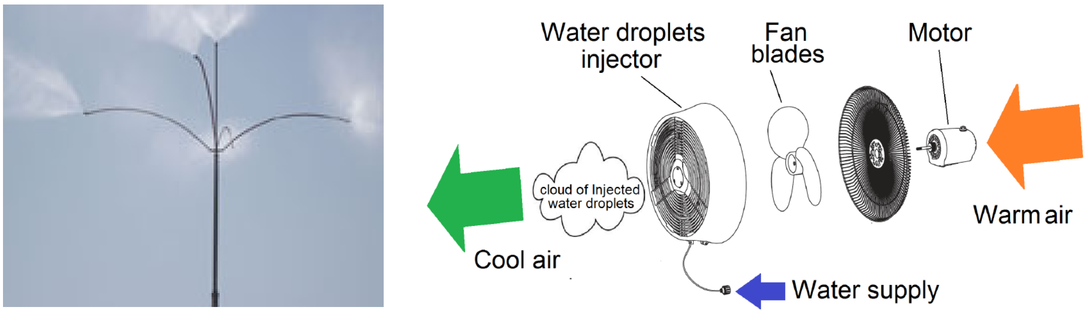
[14] Personal notes during Haj period, Mecca, Saudi Arabia 2002, 2004
[15] Personal inspection of HVAC markets in Basra, Iraq during different periods between 1980-2014



(a) (b)

Figure 3.4: (a) mist pole (in Mecca, Saudi Arabia) (b) MF basic parts [139].

The selection of an HVAC appliance is highly dependent on the weather and socio-economic status. New technologies are under development motivated by energy efficiency, such as incorporating storage with COs to enhance performance through a reduction in the amount of humidity [140], determining optimal water-spraying density [129], improving water use efficiency, extending life, easing maintenance, reducing the dependency on grid power [141], [142] and even spraying of roofs as an indirect air cooling technique [137], [143].

COs (including MFs) owing to low cost, low power consumption, higher energy efficiency, and acceptable cooling, play an important role in DSM strategies. COs are used widely in hot yet dry weather areas and have been the subject of a significant amount of research. [144] assert that COs can provide considerable energy savings (3 kW/air cooler) whilst at the same time provide an adequate level of cooling. [124] emphasise the effectiveness of CO as an environmentally friendly air cooling system due to their small carbon footprint and working principle. [126] investigate the application of indirect COs in domestic cooling loads in Iraq. [122] study the use of COs from a human comfort perspective while [120] and [121] explore the applications of COs in China.

Research has proposed the use of a combination of ACs and COs. A hybrid HVAC appliance comprising an AC with a CO has been produced - as an experimental proof-of-concept device - in a single-package two-stage (CO-AC) residential HVAC appliance – HybridAir – driven by the goal of harnessing the advantages of both [145]. Another approach is to inter-operate a large size CO with an AC such that when the CO becomes incapable of meeting the desired level of comfort, the CO is switched OFF and the AC turned ON [132]; this strategy has been deployed in several large buildings in four different Indian cities. The conclusion is that the technique is economically feasible in all spaces except in low density offices, Table 3.1 summarises the conclusions.

This research will harness AC-CO-MF interlocking as one element of the solution to provisioning sufficient power to provide an adequate level of air cooling and conditioning during cyclic blackouts. Evidence supporting the effectiveness of the approach is provided later in the dissertation.

Table 3.1: The financial feasibility of interlocking large capacity ACs and COs in large buildings and complexes [132].

	High density office	Low density office	Movie theatre	Waiting hall
City of Akola	✓	×	✓	✓
City of Bangalore	✓	✓	✓	✓
City of Delhi	×	×	✓	✓
City of Indore	✓	×	✓	✓
(✓) feasible (×) not feasible				

3.5 Distributed Generation

DG has been proposed as a potentially robust solution to a range of power system problems. DG has been referred to as ‘Embedded Generation’, ‘Dispersed Generation’, and ‘De-centralised Generation’ and spans a spectrum of different ratings ranging from several kilowatts to 300 MW[16] depending on the country and its legislations, standards, and regulations. The introduction of a range of new smaller, modular power generation technologies, such as wind turbines, Photovoltaic (PV), fuel cells, micro gas turbine, biomass, Stirling engines, ocean energy and geothermal, has been the trigger for the evolution of DG. Selection of the most appropriate DG depends on a mix of factors such as capital cost, efficiency, fuel cost, maintenance costs, size, weight, emissions and noise. DG is

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[16] As in the case of Germany.

defined as an electric power source connected directly to the distribution network or on the customer side of the meter; for a detailed discussion of various DG definitions refer to [146].

3.5.1 Distributed Generation Penetration

Several factors fuel the increased penetration of DG throughout current power systems [147], [148], [149]:

1. **Environmentally-friendliness: r**enewables are viewed as a viable route to reducing GHG emissions
2. **Reduction in Investment:** DG in general requires less investment than large, centralised power plants and enjoy faster payback periods since it is possible to install just sufficient generation to fulfil a specified demand. The proximity to customers eliminates the need for grid expansion which reduces the overall investment.
3. **Customer Participation:** a mix of customers are motivated by the incentives offered by governments and utilities displacing some of the investment burden
4. **Transmission Loss Reduction:** losses in generated power ranges from 7% in western countries [148] to 35% in countries like Iraq [4]; local DG systems restrict the need for long distance transmission lines thus eliminating all associated losses
5. **Increase Resilience to Outages:** installing ‘within-the-premises’ DG offers variable size islanding during faults and blackouts thus providing increased supply reliability which in turn helps manage blackouts, brownouts and cyclic blackouts.
6. **Increased Power System Security**: DG compromises a plethora of generation technologies operating on different principles increasing the security of the power supply and reducing the dependency on imported fossil fuel; thus the resilience of the system is enhanced.
7. **Increased Fuel Efficiency**: the introduction of new technologies increases

the efficiency in the use of all types of underutilised energy e.g. heat during the power generation process such as Combined Heat and Power (CHP). DG operation is much more efficient than centralised power generation.

3.5.2 Distributed Generation Applications

The main applications [150] of DG can be summarised as:

1. **Combined Heat and Power**: two thirds of all the used fuel to produce electricity is lost as heat, locating the generation plant near customer premises enables the potential to derive benefit from this heat; otherwise it is completely lost.
2. **Peak Clipping**: during peak hours DG can be used to support available load without the need for using expensive peakers or buying costly power from markets.
3. **Grid Support**: the large number and penetration of DG provide valuable services to the grid and cover shortage during different daily activities. Services include maintaining grid reliability through voltage and frequency stabilization; reducing required reserves; relieving transmission network congestions and reducing its losses; reducing overall GHG emissions by using clean DG such PVs and fuel cells, reducing the reliance on fossil fuel; providing adequate reserves; and reducing the need for new investments in generation and transmission.
4. **Islanding:** the wide spread of DG systems over wide areas unlocks the ability to support local neighbourhoods during grid instability, power shortages periods, or blackouts by isolating the area and their loads from the grid and initiating a local powering process forming a power island.
5. **Standby Power Sources**: standby power generators are installed in the premises of certain customers either because it is a mandatory requirement or because losing power is not an option for that customer due to the sensitivity of his application. Despite their installation and running costs, standby generators are rarely used, highly underutilised, not considered a

generation asset until recently, and isolated from the grid. Despite this more and more standby generators are being installed; it is estimated that there is ~170 GW of underutilised installed standby generation capacity in the USA in 2010 [43] compared with 40 GW of installed standby generation in 1999 [150]. Recently researchers and utilities have begun to consider using these assets for peak load reduction by offering their owners certain incentives in the form of payments or special discounted prices in return of using their standby generation for limited periods of time throughout the year (typically less than two hundred hours per year). Standby generation can be an influential factor in any power management strategy aiming at solving current power system challenges.

3.5.3 Distributed Energy Resources

It is important to distinguish between DG and distributed Energy Resources (DER), which is an extension of DG principles but includes consumer loads, in so doing achieving various grid services and DG intermittency compensation through a range of DR measures. A number of definitions exist and although they differ in the wording, they deliver the same meaning. [151] define DER as demand- and supply-side resources that can be deployed throughout an electric distribution system (as distinguished from the transmission system) to meet the energy and reliability needs of the customers served by that system. DER can be installed on either the customer side or the utility side of the meter. [152] define the term as a number of technologies collectively referred to as DERs i.e. CHP, solar PV modules, small wind turbines, other small renewables, heat and electricity storage, and controllable loads. Yet IEEE in its standard (IEEE-1547-2003) excludes controllable loads from its definition of distributed (energy) resources; it defines distributed resources as "sources of electric power that are not directly connected to a bulk power transmission system. DER includes both generators and energy storage technologies." [153], [154]

3.5.4 Diesel Generation

Due to their widespread deployment, a brief introduction of diesel generators is necessary. A diesel generator set is a well-established, simple, easy to maintain, reliable electric power generation technology [155]. A diesel generator consists of a diesel engine, electric generator, and all the necessary operational and control devices. Sizes range from a fraction of kW to multi-MW units. Three main factors affect their performance; their power rating, ambient temperature, and installation altitude. There are three power ratings for diesel generators; Prime, Standby, and Continuous. The Caterpillar Performance Handbook [156] defines standby power rating as the output available with varying load for the duration of the interruption of the normal source power. Average power output is 70% of the standby power rating. Typical operation is 200 hours per year, with maximum expected usage of no more than 500 hours per year. The prime power rating is defined as the output available with varying load for an unlimited time. Average power output is 70% of the prime power rating. Typical peak demand is 100% of prime rated with 10% overload capability for emergency use for a maximum of 1 hr in 12 hrs. Overload operation cannot exceed 25 hours per year. The Continuous Power Rating is defined as the Output available with non-varying load for an unlimited time. Table 3.2 summarises these definitions.

The controlling factor is the ‘type of load’ which is ‘variable’ for the first two and ‘non-varying’ in the third. A generator running in prime mode can supply 100% of its rated power but not continuously because it runs only in ‘variable load’ while a continuous one can support 100% of a ‘non-varying load’. Different operation modes do not imply different types of generators for each operational mode; on the contrary, same generators have both standby and prime ratings at the same time.

Finally, as the altitude on which a generator is installed increases the amount of available oxygen becomes less which affects fuel combustion reducing efficiency. For temperature, higher ambient temperatures cause loss of efficiency. In both cases generator de-rating is need. Generator de-rating refers to the need to lower a generator's rated operating capabilities due to an environmental reason or a load affect [157]. This situation requires the use of a larger generator than what is necessary under normal conditions.

Table 3.2: Diesel generation power rating comparison [156].

Parameter	Power rating		
	Standby	Prime	Continuous
Type of load	variable	variable	Non-varying
Average supplied power	70%[17]	70%[18]	100%[19]
Typical peak demand	100%[20]	100%[21]	100%[22]
Duration on variable load (hr/yr)[23]	200	unlimited[24]	unlimited
Maximum expected usage (hr/yr)	500	unlimited[25]	Unlimited
10% Overload duration (hr/yr)	none	1 in every 12[26]	None

3.6 Micro-Grids

Micro-grids evolved as a potential robust solution to the problem of managing the emergence of distribution generation into legacy power systems. A micro grid can be defined as a low-voltage distribution network located downstream of a distribution substation through a Point of Common Coupling (PCC)[27] which hosts a variety of components including distributed generators, distributed energy storage (DES), and controllable loads [149]. The population of various components in a micro grid are connected to a LV power distribution network through their own controllers. A micro-grid central controller (MGC) installed at the MV/LV local substation and used to bridge the micro-grid to the grid performing

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[17] Of standby power rating
[18] Of prime power rating
[19] Of continuous power rating
[20] Of standby power rating
[21] Of prime power rating
[22] Of continuous power rating
[23] Hour per year
[24] For 70% output power
[25] For 70% output power
[26] Not to exceed 25 hrs/year total.
[27] According to the IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems standard (IEEE Std 519-1992) PCC is defined as "the interface between sources and loads on an electrical system". [257]

connection/separation operations to/from the grid during its operational modes. The MGC is connected hierarchically to all generation, local load controllers (LC), and Generation Controllers (GC) through a communication infrastructure so that it can perform all monitoring and control operations over the entire micro-grid. The micro-grid is managed and controlled through mutual cooperation, set-point adjustment, and status related data exchange between the MGC and all LCs and GCs during their quest to support local loads with the available supply. The approach may comprise of various DSM, and if necessary load shedding, operations in both normal and emergency situations [158]. Figure 3.5 shows the architecture of a typical micro-grid. All micro generation resource types need not be in all micro-grids; they are included for demonstration purposes only.

In general, a typical micro-grid works in either grid-connected or autonomous (islanded) modes (or in the transition stage between them) [159]. In the grid-connected mode, DG supplies power to the grid, while in the autonomous mode DGs supply power to support local loads within the micro-grid's area during blackouts and brownouts with or without DSM measures through energy storage devices and controllable loads. If this is not possible load shedding becomes inevitable. Partitioning the grid into smaller segments (sub-networks) effectively creating autonomous micro-grids in the form of islands is an effective strategy to power as many loads as possible during outages or severe power shortages. The technique isolates the fault in a much smaller area making restoration much faster.

Finally, it is worth noting that the majority of DGs in micro-grids are renewables which are operational continuously and not only during contingencies, all are active regardless of having a power shortage/outage or not.

3.7 Agent-based Distributed DSM

Due to the distributed nature of power system demand, choosing a distributed DSM solution is more suitable than a traditional centralized approach. Agents provide a core foundation in such solutions.

3.7.1 Agents

Due to the importance of agents, a detailed discussion of all their related aspects are given in the following sections

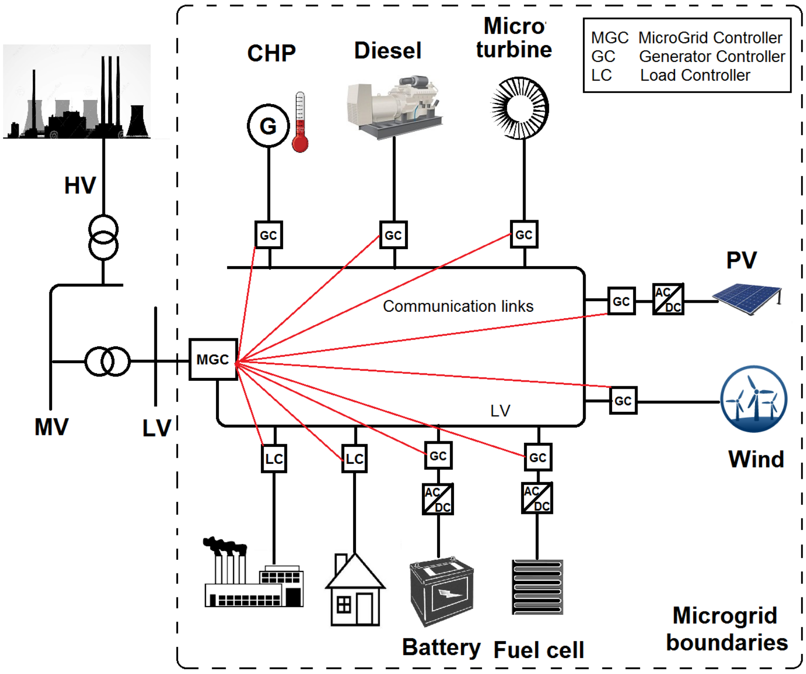

Figure 3.5: The basic structure of a typical micro-grid.

3.7.1.1 What is an Agent?

[160] state that the availability of a wide spectrum of different agent definitions is evidence of the difficulty surrounding an exact description of an agent. Currently agents drive many system applications ranging from social sciences to engineering and although numerous systems are built around them, there is no single definition that is accepted universally. Among this plethora of definitions [161] define it as a computer system (hardware or software) situated in some environment and capable of autonomous action in order to meet its delegated objectives; whilst

according to [162] an agent can be defined as anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors. [160] adopt the definition of [161] and conclude that “while all the definitions referenced above differ, they all share a basic set of concepts: the notion of an agent, its environment, and the property of autonomy”.

Although general agreement exists that autonomy is central to the notion of an agent, there is little agreement beyond this in great part owing to the fact that various attributes associated with agency are of differing importance for different domains. Thus for some applications, the ability of the agent to learn from their experiences is of paramount importance; for other applications, learning is not only unimportant, it is undesirable as in the case of an agent-based air-traffic control system that change its behaviour through learning new tactics at run-time.

3.7.1.2 Intelligent Agents

An intelligent agent has four distinguishing attributes [163], [160], [164]:

- **Autonomy:** an agent should be able to schedule action depending on its own observations about its environment
- **Reactivity:** an agent should have the ability to sense changes in its environment and react to them
- **Pro-activeness:** an agent should have the ability to behave and change its behaviour in the right way to achieve its goals
- **Socialability:** an agent should have the ability to interact with other agents in its environment

An agent should have perception of its environment and its inhabitants, decision making, and execution of proper actions. Agents can represent simple and complex entities, [165] gives an example of the possibility of using an agent to represent a simple light switch; using agents to represent simple actions and operations can be justified if there are other motives for such use, such as consistency with the remainder of the system or if it is just the first version of an upgradable design.

3.7.1.3 Agent Environment Properties

Agent environments are classified to certain characteristics [162]:

1. **Accessibility:** environments in which the agent population can access all the required information, while inaccessible ones provide part of their and their inhabitants' status to each one of their agents. Real-life environments are inaccessible.
2. **Determinism**: a non-deterministic environment in which all or part of actions taking place have one or more possible consequences, i.e. there is no single guaranteed effect, as opposed to deterministic in which each action has one single determined effect. Real-life environments are non-deterministic.
3. **Dynamics:** environments can either be dynamic through changes initiated by agents and other influential processes, working outside agent control, acting in that environment or they can be static under total control of their population of agents and any action taking place in them is the consequence of their agents' actions. Real-life environments are dynamic by nature.
4. **Continuity**: environments are either discrete or continuous, in the first there is a finite number of actions while in the other there is not. Real-life environments are continuous.

Figure 3.6 shows an agent society in a real-life environment.

3.7.2 Multi-Agent Systems

The emergence of renewables and their impact on power systems both as significant generation capabilities such as wind farms or as small scattered domestic stand-alone units such as domestic PV systems, stimulated the need for distributed control. Techniques such as Multi-Agent Systems (MASs), clustering, and distributed DSM started to attract a lot of attention. A MAS also has many definitions, among those [166] define it as a system composed of multiple intelligent agents that interact to solve problems beyond the individual capabilities or knowledge of each individual.

Moreover, [160], [164] define a MAS as a system having two or more intelligent agents with inter-agent communication capabilities aimed at specifying the system goals through their interaction to satisfy their own local goals which are sub-parts of the systems goal.

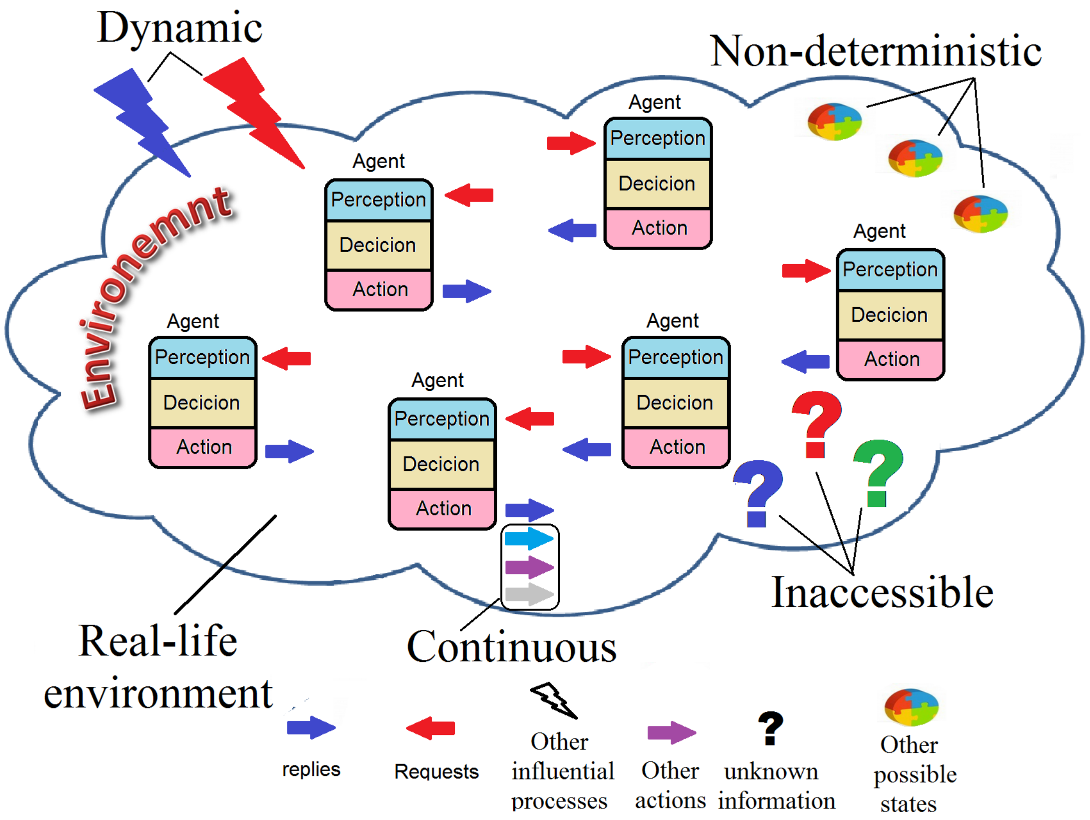

Figure 3.6: Agents reacting in their environment.

3.7.2.1 Motives for MAS Recruitment

MAS have several attributes and abilities relevant to solving a range of challenges in a number of application sectors [167]

- ability to solve big problems by a single entity due to scarce resources or performance bottlenecks
- ability to provide a naturally distributed solution that aligns with distributed problems (distributed interacting actors, distributed resources, distributed expertise, or distributed information sources).
- ability to provide enhanced features such as

  - computational efficiency (due to computational concurrency),
  - reliability (the loss of one agent will not hinder the system),
  - extensibility (due to the possibility of altering the number of recruited agents for performing a certain task)
  - robustness (increases the system's ability to tolerate uncertainty due to its distributed information sources)
  - maintainability (due to its modular agent-based structure it becomes easier to maintain)
  - responsiveness (due to its distributed nature, an agent-based system becomes faster in responding to abnormal situations)
  - flexibility (can solve complex problem due to the unique capabilities of each agent)
  - reusability (same agents used in one application can be recruited to solve another problem without rewriting them again).
- provides a means to integrate legacy systems and newly generated software

3.7.2.2 MAS Characteristics

MASs have characteristics that distinguish them from centralised equivalents and provides the drives for their use as effective distributed problem solving tools [167]:

- Each agent has limited capabilities and information that limits its capability to solve the entire problem alone
- The unavailability of a global system control mechanism capable of fulfilling systems performance requirements
- The distributed nature of the system data
- The asynchronous nature of the computation

3.7.2.3 MAS Challenges

Despite their importance and versatility, MASs impose serious challenges that must be addressed [160], [164], and [167]:

- formulisation of agent-based problems, distribution of tasks, and composing a final result from the outcome of multiple agents
- selection of the most suitable communication languages, procedures, protocols, amongst a heterogeneous group of agents.
- the design of suitable platforms to implement agent-based solutions and at the same time design platform-independent agents. The development of toolkits that produce such agents, the standardisation of available data, and interfaces to acquire, analyse, store, and respond to all types of data.
- solving potential agents' conflicting interests and viewpoints and enable an agent to understand good and bad intentions, analyse strategies, and the plans of other agents with the ability to cooperate and coordinate tasks.
- Guarantee the security of agents, their societies, and their environments from attacks, unauthorised data manipulation and transfer, and change of strategies, intention, and goals.
- to enable agents to act reasonably, in harmony with other agents, take coherent decisions and effective measures, sharing resources in a fair way whilst avoiding all actions that jeopardise overall system stability.

3.7.2.4 Benefits of MAS in Power Engineering Applications

MASs have a considerable potential in solving many power engineering problems and in designing applications, systems and solutions [160], [164]:

- the ability to design flexible systems able to respond to dynamic situations through cooperation, coordination, and negotiation
- the ability to add more functionalities to current systems through, for example, adding new agents without the need for major re-implementations
- the ability to provide systems with enhanced fault tolerance capabilities due to the distributed nature of its tasks, duties, and responsibilities
- the ability to re-use previous designs and evaluated agents in other systems without the need to re-write them provided that the communication means

and protocols is consistent in both the old and new systems

- a solution to naturally distributed problems based on their ability to represent the natural world with its interacting entities

3.7.3 Typical Agents in Demand Response

Researchers have defined, created, and implemented various types of agent for various use cases but, even if definitions differ, all have tried to map the basic structures and the influential elements in traditional DR problems which are generators, consumers, controllers, and sensors [148], [168], [169], [170], [171], [172], [173], [174], [175], [176], [177], [178], [179], [180], [181]. The most common agents amongst them are, but not limited to:

- **Load Agents:** used to control various types of general and specified loads e.g. Appliance Agents, Device Agents, and Circuit Breaker Agents.
- **Supply Agents:** play an important role in monitoring and controlling the supply of electric power, e.g. Generation Agents, DER Agents, Storage Agents, Micro-Source Agents, Composite Energy Storage System Agents[28], and Substation Agents.
- **Market Agents:** manage different aspects of power market dynamics, such as aggregating biddings, selecting and publishing prices among many others e.g. Market Operator Agents, Auctioneer Agents, Concentrator Agents and Aggregation Agents.
- **Strategy Agents:** represent major strategy deciders in the system e.g. Distribution Network Operator Agents, Utility Agents, and User Agents.
- **Network Agents:** control transmission and distribution networks and represent their operators e.g. Bus Agents[29], Point of Current coupling

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[28] Controls batteries and super capacitors

[29] Used to monitor bus parameters such as voltage and phase

Agents[30] in [177], [178], and [179].

- **Control Agents:** responsible for performing different control tasks e.g. Objective Agents[31], User Agents, Supervisory Control And Data Acquisition (SCADA) Agents, Micro-Grid Manager Agents[32], Quality Control Centre Agents[33], DSM Agents, Control device Agents, House Agents[34], Cluster Head Agents [35], Administrative Agents [36], Main Controller Agents, Management Agents, Power Converter Building Block Agents [37], Regional Control Agents[38], load control Agents, and Sensor Agents.
- **Data Handling Agents:** the preparation of data and performing various data processing activities e.g. Data Analysis Agents, Database Agents, and Load Forecasting Agents.
- **'Other' Agent Types:** many other types of agents have been used for a range of purposes e.g. Real-Time Digital Simulator Agents[39], Schedule Coordination Agents[40].

3.7.4 MAS-based Distributed Load Control

The flexibility of MASs and their ability to offer distributed solutions has prompted the use of agents in systems implementing distributed load control. Various MAS based systems have been proposed in the literature covering different fields, among those:

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[30] Used to monitor voltage, frequency, and phase and isolates or reconnect the micro-grid from the grid in case of power contingency
[31] Specifies clusters in the PowerMatcher
[32] Used to control a micro-grid
[33] Agents used to manage a QCC including generation, storage, and processing infrastructure
[34] Local house controller that controls all or part of the appliances in the house
[35] Represents a cluster of agents of its own kind and makes all communications
[36] Acts as a central controller orchestrating other agents
[37] Used to monitor power, current and voltage of a PCBB to control its operation
[38] Controls a group of load agents in its region
[39] Used to send and receive commands to/from a real-time digital simulator.
[40] Used to find power schedule in a power market

3.7.4.1 PowerMatcher (Supply-Demand Matching)

The PowerMatcher is an early example of SDM systems [148]. It is a market-based multi-agent distributed Smart Grid oriented energy management system targeted at managing the impact of renewable intermittency on the supply of power through micro-economics-based[41] operations within a dedicated power market developed for this purpose. The PowerMatcher has its own communication protocol and architecture with the ability to consider both conventional and non-conventional (renewable) energy sources, represented by thousands of small intermittent energy producers, and sinks. The system hosts a variety of small and large energy producers and consumers and can manage all types of dispersed small and large renewables such as domestic wind turbines and small solar systems, large wind farms, and off-shore wind-based generation facilities. All consumers are clustered to form a uniform population of energy-related participants treated as a single generating – consuming entity with the ability to change its consumption according to the production level, matching demand with the available intermittent supply. The system is based on a dedicated power market in which generated power is sold and purchased through clustered DGs supported by energy storage facilities, instruments and responsive distributed loads, all operating in harmony in one or more Virtual Power Plants[42] (VPPs) through which energy balancing is carried out.

Figure 3.7 shows a typical PowerMatcher configuration [182]; the system is based on several types of agents:

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[41] Micro-economic is the "study of the economic behaviour of individual units of an economy (such as a person, household, firm, or industry) and not of the aggregate economy (which is the domain of macroeconomics). Microeconomics is primarily concerned with the factors that affect individual economic choices, the effect of changes in these factors on the individual decision makers, how their choices are coordinated by markets, and how prices and demand are determined in individual." [260]

[42] A virtual power plant (VPP) is a cluster of dispersed generator units, controllable loads and storage systems, aggregated in order to operate as a unique power plant. The generators can use both fossil and renewable energy sources. The heart of a VPP is an energy management system (EMS) which coordinates power flows coming from generators, controllable loads and storages. The communication is bi-directional, so that the VPP can not only receive information about the current status of each unit, but it can also send signals to control the objects [259].

1. **Objective Agent:** give a certain cluster of agents its purpose, e.g. working as a Virtual Power Plant. If no objective agent exists, then the objective of the cluster is to match demand to an affordable supply.

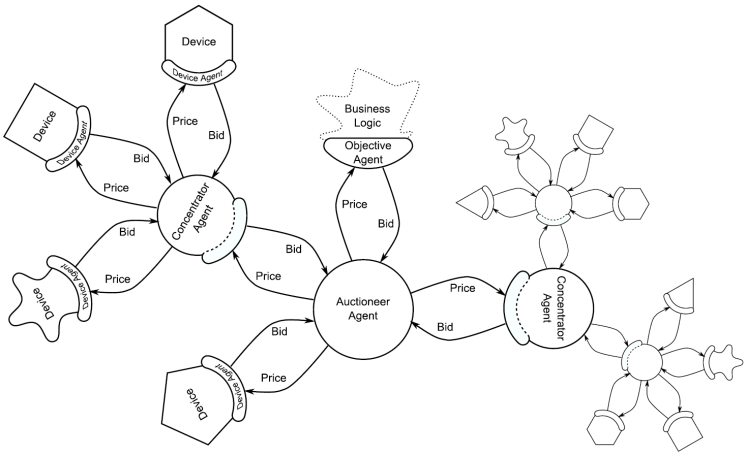

Figure 3.7: A typical PowerMatcher configuration [182].

2. **Auctioneer Agent:** the purpose of this agent is to move to the equilibrium price[43] for the overall population.
3. **Device Agents:** operate devices in the most economically optimum manner through power purchase-sell operations without affecting the nature of the device or its working principles. Device Agents have the ability to negotiate with each other and with their dedicated Concentrator Agent. Several types of devices are active in the PowerMatcher [148] such as;
    - stochastic generation devices e.g. PVs and wind turbines
    - shiftable operation devices e.g. pool pumps
    - user-dependent devices e.g. audio
    - fully-controllable generators e.g. diesel generators
    - electricity storage devices e.g. batteries
4. **Concentrator Agent:** a ‘cluster-head-like’ agent responsible for aggregating all bids for power and unification into one bid, sends it to the auctioneer agent,

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[43] The equilibrium price is the power price when the marginal costs of the producer (fuel cost to keep the power unit operational) equals the price that the last consumer is willing to pay [252].

receive offers, and distributes the offers among all its cluster members.

Auctioneer agents and concentrator agents form a pool market from which all power needs are fulfilled and SDM is achieved by various measures such as load shifting and load fragmentation performed by device agents.

The full potential of the system has been validated through a series of small scale evaluation studies [183], [184], [185], [186], [187], [188], [189] concluding with the establishment of a limited size smart grid - PowerMatcher City - operating effectively on 25 dwellings located in the Netherlands [168]. Each house has a 14 m^2 of PV panels, 2 electric vehicles, one 5 kWh battery grouped as a real-life test-bed equipped with one 2.5 MW wind turbine. All houses are equipped with Smart Hybrid Heat Pumps and various Smart Appliances, all under the control of PowerMatcher software and function as a single VPP [182], [190], [191]. The success of the project has stimulated PowerMatcher City II which comprises more houses and new intelligent appliances [192]. For more detailed information on both projects refer to [168], [192], [193].

3.7.4.2 Intelligent Distributed Autonomous Power System (Customer-Owned DER)

The Intelligent Distributed Autonomous Power System (IDAPS) [169], [170], [171], [172] is defined as a specialized multi-micro-grid agent-based power management system for coordinating ‘customer-owned’ distributed energy resources aimed at securing power for customer-defined critical loads during power blackouts and allocating any surplus power to non-critical loads. The IDAPS concept includes intelligent agent based architecture for a co-operative multi-micro-grid autonomous power system capable of finding the type and optimum rating of generation needed to support critical loads [170]. IDAPS divides the power system into several feeder-based micro-grids, each one consisting of available DGs, loads, customers, supporting devices and a web-based communication infrastructure to enable components to inter-communicate. Areas without DG require a new DG with suitable rating to be installed [169]. During power outages, IDAPS islands its micro-grid from the grid and supports its critical loads from local DG; if this is not feasible, power is purchased from neighbouring IDAPS-member micro-grids according to ‘supply-driven demand management’ since the demand in an IDAPS micro-grid can fluctuate and be hard to forecast in advance making the usage of the traditional demand-driven-supply not feasible [171].

In the supply-driven demand management scheme the demand is powered by the available supply, which in turn implies the use of various DSM operations to shift, trim, or shed demand so that it matches the available supply taking into account the power price. For this purpose, a bulletin board based power trading mechanism is established which allows end-users to buy power or not to meet their deferrable demand. IDAPS recruits a series of agents to perform its management activities such as; user, DER, database, aggregation, control, bulletin board, load, device (relays, circuit breakers), data analysis, and management agents [171], reduced to four only in [172] in later implementations i.e. DER, Control, User, and database agents. IDAPS performs price-based DSM on its grid-connected population securing critical loads, shedding non-critical low priority loads allowing its community to share the locally available power [172]. IDAPS suffers from certain drawbacks:

1. The assumption that the installed DERs is equal to the overall critical loads and the need for more investments to add new DERs where none exists
2. The intermittency of some DER is not considered explicitly, such as the case of a blackout happening at night in a PV dependent microgrid. In such case, there is not enough power to support critical load.
3. Empowering to each customer the freedom to define what is critical and what is not may lead to wealthy customers dominating the majority of the offered power leaving poorer end users with power at high prices.
4. The dependence of the proposed system on ‘customer-owned’ power resources makes it only applicable to areas having considerable amount of such systems which is not the case in many geographies.
5. In hot geographies air conditioning is the critical load, which makes it hard to cover.

3.7.4.3 Flexible, Reliable and Intelligent Electrical eNergy Delivery System (Multi-Level Power Quality)

The Flexible, Reliable and Intelligent Electrical eNergy Delivery System (FRIENDS) [175], [176], [194] [195] [196] [197] is a system based on an added entity to the local power system referred to as the 'Quality Control Centre' (QCC) consisting of DGs, Energy Storage Systems (ESS), data processing and power electronics (such as Active Filter[44], Uninterruptible Power Supply system, Unified Power Flow Controller[45], solid-state or hybrid-type[46] relay to control the power quality). The main aim of the QCC is to increase reliability and quality of power delivery through operation as an extensive Uninterruptible Power Supply (UPS). All QCCs are connected by a communication network used for control. QCCs are installed between customers and distribution sub-stations in a one-per-building basis in urban areas forming an interconnected mesh of QCCs which permit the re-routing of power from one QCC to another. Each QCC is capable of providing its customers with power with different levels of quality (normal quality, High quality, and super quality) during normal operations and in addition, provides standby power during power blackouts.

FRIENDS has the following advantages; flexible dispersed generation, power system reconfiguration flexibility, supply reliability, load levelling capabilities, energy conservation measures, system level DSM measures, modern automatic generation control techniques and voltage regulation capabilities. Figure 3.8 shows a typical FRIENDS configuration [198]. The difference between implementations is defined by the quality of the AC voltage signal waveform i.e. constant voltage, non-harmonics, non-interruption. The aim is to improve power reliability through a system configuration that is both flexible and adaptable by using static power electronic switches.

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[44] Filter having active components such as transistors and operational amplifiers but having no inductors.

[45] "a generalized real and reactive power flow controller that is able to maintain P and Q at a given bus on the transmission line" [254]

[46] housing semiconductor thyristors and mechanical contacts that complement each other.

The availability of DG and ESS provides the necessary means to maintain security of supply and at the same time provides the system with the resources to perform successful DSM operations. FRIENDS also provides QCC connection flexibility to more than one distribution point, useful in case of failures or faults. Each QCC has its own set of switches used to disconnect and reconnect the QCC and its neighbours to different sub-stations depending on need and a re-routing capability to reconnect the QCC population as needed.

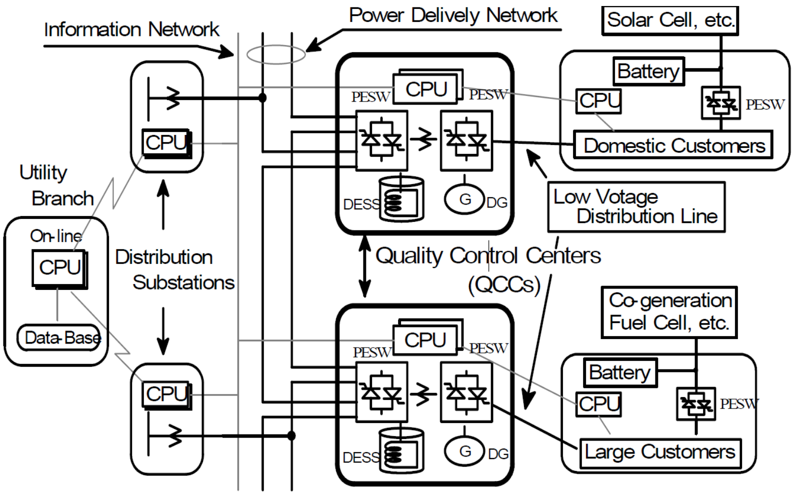

Figure 3.8: The FRIENDS concept [198]. [47]

FRIENDS utilizes agents [175], [199] due to the distributed nature of the problem, reducing the volume of computation through distribution amongst all agents. An agent is assigned to each local distribution sub-station and to each QCC.

The main disadvantages of FRIENDS are; installing the required DGs and ESS is costly and securing this amount of capital is a challenge; a case has not been made for offering multi-quality level power; it is neither easy nor cheap to reconfigure the QCC whenever a new customer is connected.

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[47] PESW: Power Electronic Switch, DESS: Distributed Energy Storage System

3.7.4.4 Rokkasho Project (CO_2 Free Micro-Grid)

Rokkasho village is connected to wind farms supplying 51 MW and with 34 MW battery storage facilities to mitigate supply fluctuations of the wind turbines. The project is a CO_2-free micro-grid demonstration, complementing previous CO_2 emitting renewable-power source projects [200] such as the Aichi [201], Kyotango, and Hachinohe [202]. The main aim is to develop necessary technologies and to evaluate the potential to operate a micro-grid successfully using only renewable energy resources by overcoming their weather-dependent supply intermittency. Figure 3.9 shows the facilities and configuration.

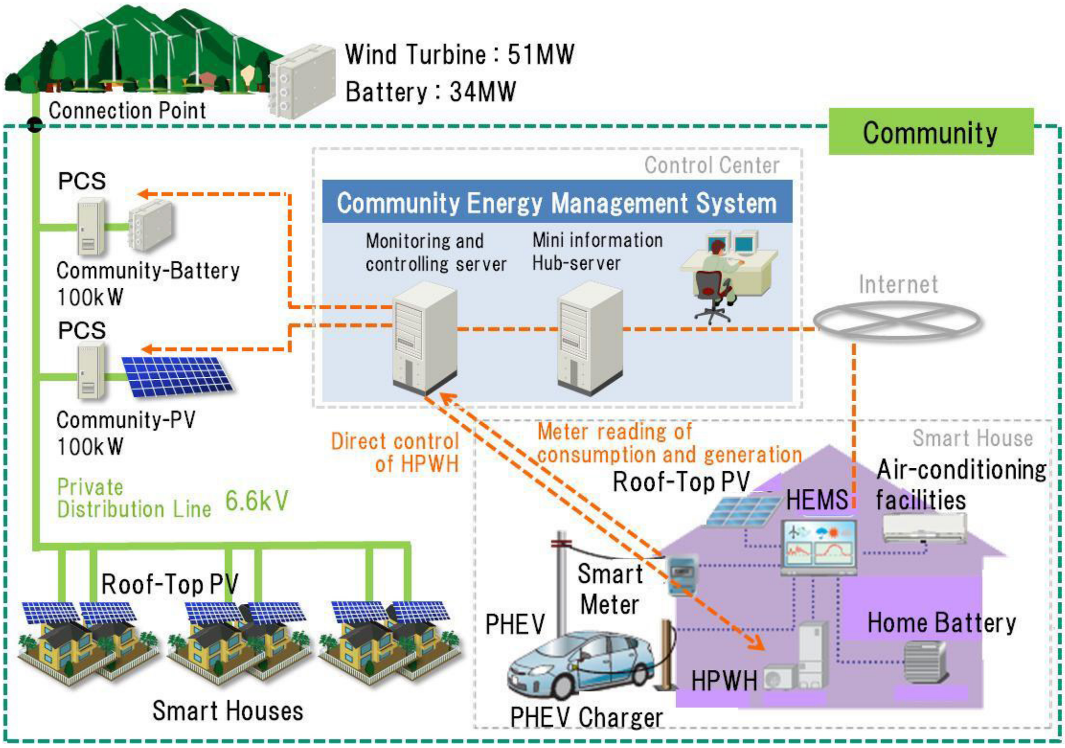

Figure 3.9: Rokkasho project configuration in demonstration site [200].

The micro-grid includes six smart houses, each with 27.4 kW PV system, Heat Pump Water Heater[48] (HPWH) with tank storage, Plug-in Hybrid Electric Vehicle (PHEV) and charger, Home Energy Management Systems (HEMS), and a smart meter

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[48] use a compressor to move heat from outside the water heater to inside it instead of generating heat directly using a resistive element; this makes them 2-3 times more efficient than resistive ones. They work in the opposite way of a typical refrigerator.

infrastructure. In addition, there is a Community Energy Management System (CEMS), PV system, and battery storage. The CEMS controls the community battery charge/discharge operations and performs DR operations through DLC on its HPWHs population according to the forecasted supply and smart meter data that monitors consumption. It also performs SDM and updates HEMSs supply, demand, and power price data.

In the goal to match supply with demand, the project found that HPWHs were charged at night owing to the ToU prices which were cheaper at night while the installed PV was used during the day. The problem was solved by load shifting using CEMS DLC or HEMS local control. Significant results were that DLC under CEMS control was more effective than under HEMS and that DLC-controlled loads can be used effectively for load balancing. The approach also had a positive impact on the sizes of batteries and the number of charge/discharge cycles.

3.7.4.5 West-bank AC Load Shedding System (Selective AC Load Shedding)

One of the projects that uses air conditioning load shedding to shave demand peaks is the WACLSS proposed and implemented by [11] (see Section 3.3.5). Compared to the previous systems, WACLSS has the following features:

- a simple yet effective structure, which makes it easy to install and maintain
- needs low investments since it uses available infrastructure, such as the ADSL network and smart meters
- exploits the mild Mediterranean weather and in turn the usage patterns of ACs, the size of active AC population and the degree of inhabitants' dependency on AC appliances. Thus low AC shedding time results without jeopardising the customers' level of comfort.
- highly scalable, since only the installation of a local controller is needed to activate new customers.

Table 3.3 summarizes the main attributes of these systems.

3.8 Power Rationing

Rising power demand forces many developing and developed countries to undertake various rationing [204] measures through voluntary and mandatory power supplies restriction by offering limited power to customer through contracted power schemes and load shedding. Under restricted power supply regimes, utilities offer power within predefined bands throughout the day and night, as in the Italian case [203] where each customer is provided maximally with either 3 kW or 6 kW of power through contract with the power provider. Each power supply level has its own tariff; 5.13 €/kW and 14.44 €/kW respectively in addition to a basic cost which equals to 6 €/year for the first and 23.45 €/year for the second [204]. Similar measures have been taken in both Portugal [205] and Nepal[49]. In the former, different power levels have been supplied to customers during different periods throughout the day, while in the latter two types of continuous power supply is provided, a limited guaranteed supply used to power base load appliances and another non-guaranteed supply used to power other loads. In all cases, power is delivered to all customers according to signed agreements with the utilities. Any violation is penalised by power outages until the demand falls below the contracted threshold.

Furthermore, two main types of load shedding are in common use; total and AC appliance based. In the first, unlimited supply of power is provided to all customers for some time then power is turned OFF for another period, and this is repeated periodically. The length of the ON and OFF period depends on the size of the area, size of their demand, and the amount of available power and as it becomes scarcer, the length of the power OFF period becomes longer and of the ON period shrinks by the same amount. With the second approach, not all the residential load is shed and instead high loads such as HVACs are shed leaving the remainder operational

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[49] Information provided by Dr Nigel Goddard, Director of the Institute for Adaptive and Neural Computation, School of Informatics, University of Edinburgh during a TEDDINET Workshop held at the University of Nottingham 27-28/4/2015.

Table 3.3: A comparison of MAS-based Distributed Load Control approaches.

	Control method	**Agent-based**	**Distributed**	**Needs high investments**	**Power market-based**	**Simple**	**Implemented**	**Utilizes storage**	**Handles renewables**	**Micro-grid-based**	**Test-bed**	**For standby purposes**	**Perform DSM measures**	**Power routing**	**Main Attributes**
1	Power Matcher	✓	✓	✓	✓	✗	✓	✓	✓	✗	✓	✗	✓	✗	DSM-based, Agent-based, Supply-demand matching, targets renewables' supply fluctuations, needs a dedicated power market, for continuous operation, Implemented in a real-life test-bed
2	IDAPS	✓	✓	✓	✓	✗	✗	✓	✓	✓	✗	✓	✓	✓	Targets customer-owned DERs, agent-based, micro-grid-based, supply-driven DSM, needs a dedicated power market, prioritizes demand
3	FRIENDS	✓	✓	✓	✗	✗	✗	✓	✓	✓	✗	✓	✓	✓	Can be used for standby purposes, system-level DSM, complex, expensive, provides multiple power quality levels, provides power re-routing, needs QCC
4	Rokkasho	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✗	✓	✗	Micro-grid-based, DSM-based, Implemented in a real-life test-bed, centralized, for continuous operation
5	WACLSS [50]	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	Selective AC load shedding, simple, ON/OFF DLC only, for peak clipping purposes

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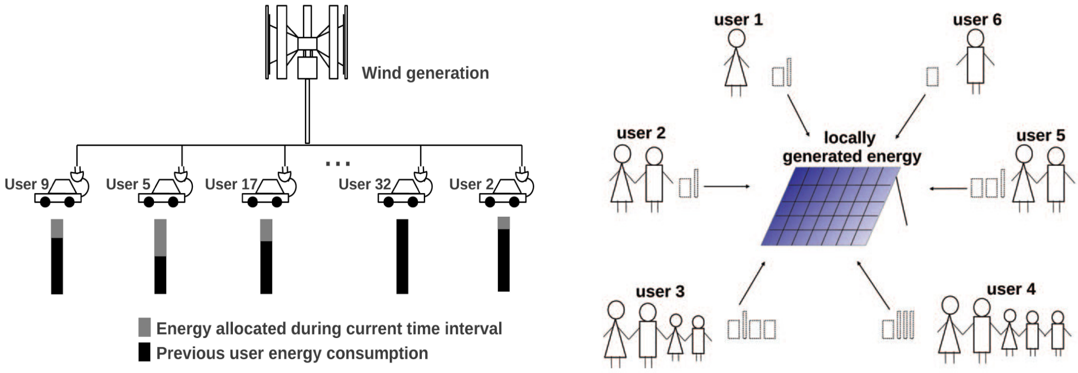
[50] WACLSS hardware was built and tested but full deployment hasn't been done.

[11]. The last case provides a dynamic way of shedding heavy loads but nevertheless it is not considered as rotational load shedding.

[206] propose sharing energy from an intermittent energy supply such as a solar, wind, or even surplus excess from a certain power generation entity and distributing it in a fair way among all customers. It is noted that it is challenging to establish an effective mechanism to distribute energy resources fairly due to the intermittency of the energy supply combined with the stochastic nature of the customers demand. The researchers propose the fair rationing of the energy produced by a renewable energy source among all battery-based customer loads such as electric vehicles and energy storage systems. In [207] the same researchers propose a scheduling algorithm that aims at rationing the energy obtained from renewables fairly in order to use deferrable loads, such as dish washers, washing and tumble dryer machines, in a one at a time fashion. Loads that do not follow time specific operation patterns are chosen to ease the burden. Figure 3.10 shows the two configurations, with the focus on distributing energy in a fair way depending on customers' previous renewable energy consumption and extending the available renewable energy with grid power in case of need.



(a) Charge electrical vehicles [206]　　　(b) Power residential loads [207]

Figure 3.10: Users sharing an intermittent energy source fairly

3.9 Fairness in Demand Response

Fairness is crucial and any attempt to ration resources unfairly among a group of customers is more likely to be rejected [208]; despite its importance, fairness in DSM is a relatively unexplored research area [209]. In general, fairness in DSM concerns the allocation of a ‘power’ resource among a group of customers, in contrast to multi-resource fair allocation which is beyond the scope of this research [210]. DSM measures are used to manage available power in a logical ‘fair’ manner in order to provide a certain service to customers at a certain time. Failing to provide the same level of service to all customers for the same duration of time, or forcing them to pay differently for the same amount of power consumed are examples of unfairness to be avoided in order to embed acceptable DR-based solutions. It is thus possible to categorise DR fairness into five major categories:

1. **Energy-based Fairness:** in this scheme each beneficiary receives the same amount of energy to operate his appliances (equal shares) [206], [207].
2. **Quality-of-Service (QoS) based Fairness:** the QoS provided to each customer is set according to a certain criterion which differs from customer to another according to preferences. If the provided service, for example, is air conditioning then the quality is manifest through the thermostat setting which in turn specifies the room temperature. There are three main types of QoS fairness:
    a. **Min-Max:** the requirements (in the form of thermostatic set points) of the least demanding customers are satisfied first, then the rest are satisfied as long as there is enough power to do so, leaving the most demanding to the end if there is sufficient power to support them. An example [114] is thermostatically controlled loads such as ACs in which each customer requests a certain setting.
    b. **Proportional:** each beneficiary receives part of his requirements (in the form of a percentage) depending on the amount of available power.

    c. **Temperature:** AC usage rights are granted to hot houses while the cooler ones are given usage rights for an AC counterpart such as a CO. An example is the temperature-triggered distribution [173].

3. **Time-based Fairness:** a time-related usage right distribution criterion is adopted to allocate a certain service or a dedicated amount of power for distribution to customers. There are two types of this kind of fairness:
    a. **Usage Time:** also known as Fair share, each beneficiary receives the same amount of usage time, regardless of the amount of needed power.
    b. **Zoned Usage Time:** a derivative of the usage time fairness in which customers have the ability to prohibit the systems allocating HVAC usage right at times when their houses are empty.
    c. **Average Delay:** the average long-term delays of all shifted loads are kept the same for all customers. An example of such fairness is discussed in [211].
4. **Price-based Fairness:** energy is sold at a different price, cheaper when certain criteria are satisfied such as shifting loads to off-peak time or reducing their demand at peak time to [212], [213], [208].
5. **Occupancy-based Fairness:** energy is distributed to power HVACs depending on the number of people inside each dwelling. Larger families are permitted to operate their AC, CO, or MF for longer periods.

3.10 Summary

Many countries suffer from power shortages resulting in cyclic blackouts which have severe socio-economic consequences on their population, especially in hot geographies. Cyclic blackout mitigation consists of a set of measures aimed at reducing the demand either directly, as in load shedding, or indirectly, as in increasing energy efficiency.

Supply-side mitigation includes the utilisation of available standby generation the total amount of which is substantial whilst demand-side mitigation includes all demand side management measures, DR and energy efficiency, both proven to be highly impactful. DLC is the main technique used to remotely control a range of small and large loads within different DR strategies; using DLC to manage substantial loads can produce substantial cuts in power consumption. A communication network and an advanced metering infrastructure are essential to implement any DR strategy.

Air conditioning is the major contributor to overall demand and managing that load component is a potential cornerstone in mitigating power shortages as long as an acceptable level of comfort is maintained to customers. Evaporative air cooling using COs, MFs, and mist sprayers are air conditioning options that are well-known and popular in many hot countries. Air conditioning control can be invoked in six ways; ON/OFF, thermostatic, fan speed, thermal storage, compressor delay, and interlocking with less-power consuming counterparts. HVAC interlocking is a promising technique that has attracted little attention thus far but has substantial potential in reducing power consumption whilst providing as high as possible level of comfort to customers at little investment (Table 3.4).

DG systems are widely used in solving several key problems e.g. increasing the fuel efficiency through CHP, not feasible in many countries such as Iraq where the majority of installed DGs are diesel generators, many of which are underutilised and not fully loaded. This condition contradicts the maximum efficiency requirement of operating in highly loaded environments [214], [215], [216], [217].

Micro-grid islanding is also a technique that can provide power during blackouts, most based on the use of Agents. Various types of agents are found in the literature and are highly application-specific and are highly suitable for the implementation requirements of distributed control strategies.

Several forms of power rationing are utilized through contracted power schemes; this topic has received little attention from researchers.

3.11 The Research Gap

Power shortages are a world-wide phenomenon affecting the lives of millions of people around many developing countries. The biggest impact is on citizens living in extreme conditions i.e. in hot countries where temperatures frequently exceed 50 °C during the hot season, living without electricity causing them to suffer from socio-economic issues crippling development and prosperity. Any permanent solution must be aimed at providing sufficient power to support basic needs including air conditioning/cooling, as a minimum, under any conditions.

The upgrade of modern power system is costly and slow but careful planning of such measures with the continual goal of tailoring the demand to fit available supply is mandatory. A solution is needed to bridge the gap between the current chronic power shortages and the final goal of power self-sufficiency through satisfying these requirements:

1. minimum investments through the use of all available resources
2. sufficient power to provision customer basic power needs
3. provide an acceptable level of customer comfort

Currently there is a substantial amount of underutilised standby generation distributed in companies, private establishments and public facilities. The literature shows increasing attempts to harness those generators through binding contracts and use them to supply grid-supporting power for limited periods of time. The role of standby generation in cyclic blackout scenarios has not been studied rigorously thus far. No previous research suggests empowering standby generator owners with the freedom to specify the amount of power the owner wants to contribute for the period they specify and the ability to change the amount and duration of the contribution without any intervention or limitation from any party. The total freedom granted to owners requires the power management system to have the ability to adjust the demand to match the available supply and at the same time distribute the available power among its customer population in a fair manner.

Table 3.4: A comparison of AC load control strategies.

	Control method	**Reason**
1	Thermostat control	• Needs enough power to operate all ACs • Suitable for moderate weather or properly insulated houses. • Sometimes need a huge number of AC to control in order to have a tangible effect of demand reduction as in the case of the near-end-of-cycle technique. • In high thermostat setting, AC has no effect
2	Compressor delay time	• Need to install a compressor delay relay • Needs enough power to operate all ACs, which is not available in cyclic blackouts
3	Fan speed control	• Has very fast response • Easy to implement • Suitable for very large central air conditioning system • Operates on Multi-kW fans • Not applicable for residential AC systems
4	Thermal storage	• Applicable only for large mainly centralized air conditioning systems having chillers and equipped with dedicated storage facilities. • Not applicable to typical residential ACs • If used in large numbers it will create a new peak at chilling time (usualy at night).
5	AC load shedding	• Has instantaneous effect on reducing the demand • Has severe effect on customer level of comfort • Easy to implement • Needs little investments • Considered to be as a last resort. • Not preferable
6	HVAC Interlocking	• Suitable for cyclic blackout coverage due to its flexibility in providing multiple demand air conditioning/cooling services. • Provides good level of comfort irrespective of the available power level. • Highly flexible • Its dependency on evaporative air cooling makes it vulnerable to high humidity weather. • Needs having redundant air conditioning/cooling appliances

Harnessing power superfluity from underutilised standby generation in a dynamic way and deploying it as the main power supply stream is one element of the proposed cyclic blackout mitigation strategy. This power is supplied in variable amounts which change every few hours throughout the day and night without direct control over these resources or through any binding contracts.

Utilizing this power on-the-fly requires variable rationing through fair power sharing amongst all customers. Although setting of an upper fixed power consumption limit for each customer has been reported in the literature, no previous work has considered a dynamic scenario. Variable power distribution requires the need to ensure fairness.

Smart meters offer the dynamic ability to monitor customer power consumption and adding remotely controlled power cut-off capability to them enables them to control customers' power consumption and checking if it exceeds certain limits i.e. remote programming[51] of the smart meter to instigate new power allocation on a per hour basis and cut the ability to power OFF if the specified power allowance is exceeded is an essential part of any dynamic power rationing strategy.

The final element of the solution is the provisioning of an acceptable amount of air conditioning/cooling within a limited power budget in a fair way for every customer. Air conditioning is a major contributor to overall demand and several ways have been suggested to manage its demand such as resetting thermostats to a higher setting - a technique that is not suitable for hot countries having concrete-based housing; slowing the AC's fan speed which is effective only in central air conditioning systems having multi-kW fans; incorporating thermal storage which is

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[51] Dr Mikhail Simonov, a researcher and smart meters designer working at the Instituto Superiore Mario Boelia, Italy, during the IEEE PES ISGT 2014 conference in Istanbul, Turkey 12th-15th October 2014 confirmed the possibility of modifying current smart meter to be able to accept hourly power limit thresholds and performing local monitoring duties according to these thresholds including curtailing the power in case of breaching this power share. A preliminary agreement was reached to contact the Iraqi government to have their agreement to start to produce the first version of this meter and obtaining their permission to provide a practical test-bed to test the new smart meter during the period 2016-2018.

feasible only for large complexes operating chillers equipped with cold water or ice storage facilities. The other factor against the usage of thermal storage is that it does not reduce the daily power consumption but shifts it from peak to off-peak time. Currently shedding air conditioning loads in cyclic blackout mitigation is common; however in hot countries it is viewed as a devastating measure. The final AC control measure is HVAC interlocking, to date studied using COs to cool large buildings and complexes; if the level of customer comfort is not met, then the typical central AC is turned on. Research shows it is financially beneficial in high density offices, movie theatres, and waiting halls but not so in low-density (low-occupancy) buildings. The aim in this research is to examine the potential of interlocking COs with ACs and MFs in houses to provide by-the-budget air conditioning/cooling, flexible so that readjustments of demand according to the available supply can be made whilst at the same time providing a good level of customer comfort.

Chapter Four
Demand Coverage Strategy

4.1 Introduction

Power shortages plague millions of people worldwide and the negative socio-economic effects are crippling the development and prosperity of societies. Over the recent past, a number of costly traditional power shortage mitigation measures have been proposed, and some implemented, such as constructing new power stations; upgrading transmission and distribution networks; reducing a range of losses, and redistributing the demand to fit available supply. The implementation period for most of the solutions is long and substantial investments must be raised. This situation drives the need for transitional solutions that bridge the gap between current chronic power shortages and the ultimate goal of power self-sufficiency.

4.2 Solution Outline

The proposed solution should satisfy the following requirements:

1. target the mitigation of power shortages in residential areas since other sectors (industrial, commercial, agricultural, and public) have the financial resources to acquire and operate their own standby generation facilities
2. minimum investment through making good use of all available power resources (in this case the standby generation facilities). DG facilities, which are part of the grid, are not considered, since these are used to power other areas during the power OFF periods of rotational load shedding.
3. the targeted standby power generation facilities should remain under

the full control of owners

4. only surplus power available at these standby generation facilities is ‘snooped’ i.e. used to cover the targeted residential demand.
5. provide sufficient power to operate the basic set of residential appliances (lights, fans, televisions, fridges) and a single HVAC appliance per household
6. provide the power needed to bridge the gap during the cyclic blackout OFF periods throughout the day.
7. enable all dwellings irrespective of size and occupancy to have the same level of comfort by distributing HVAC usage rights in a fair way
8. the ability to utilise as much secured power as possible.
9. the ability to monitor customers’ demand and prevent them from drawing more than the allocated power share
10. all fulfilled without any, or with the minimum, disturbance to the grid power supply and its schedule
11. scalable both in volume and feature set

4.3 The Principle

The proposed solution is centred on integrating a blend of traditional and recently introduced techniques tuned to fulfilling the overall system goals. This is the result of pinpointing the strengths and merits of each technique compared to other alternatives, which makes it possible to place each in the appropriate role within the proposed solution. The philosophy behind the solution is based on an observation and a necessity; the observation is that in countries suffering from chronic cyclic blackouts, such as Iraq, there is an abundance of scattered, underutilized[52] standby generation and except for small domestic generators, nearly all of the remainder are continuous[53]. The scenario has evolved due to persistent long grid power OFF periods which has driven the need for standby

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[52] based on the findings of the field survey.

[53] based on personal notes during the period from 1996-2010 in several cities in Iraq.

generation that operates for extended periods of time. The basic necessity is the need for air conditioning in hot countries.

The strategy is based on a distributed agent-based mitigation system capable of providing sufficient power garnered from underutilized standby generators to operate basic appliances, including the best possible air conditioning during power OFF periods in a cyclic blackout. The foundation is the formation of two separate clusters, a static one which groups all basic load appliances in all targeted households, and a second adaptive cluster composed of different interlocked HVAC appliances (ACs, COs, and MFs one per household). All the elements of the former cluster are powered while the composition of the latter changes dynamically so that its total demand matches the available power. Two main conditions must be fulfilled while allocating the snooped power among customers: fair distribution of the power and ensuring that the unallocated segment is kept at a minimum. HVAC appliance interlocking is achieved by direct control through the house local controller connected to these appliances either through wired or wireless communication networks and appliance ON/OFF plugs, enabling the selection and activation of only one of the three HVAC appliances at a time.

Two main reasons justify the utilization of ACs, COs, and MFs together; firstly, each has a different demand, ranging from a fraction of a kilowatt as in MFs to multi-kilowatt as in ACs. Secondly, they are available in the Iraqi markets, popular among Iraqi households, and affordable. HVAC interlocking means the connection of these types of HVAC appliances in such a way that at any moment, only one is operational. The overall demand is monitored by a RSM responsible for ensuring that each household is restricted to its allocated power share. The execution is carried out by a group of distributed controllers hosting four types of software agents distributed on a per-controller basis, connected through a suitable communication network and to a central controller. The overall structure can be encapsulated in a four tier hierarchy (Figure 4.1).

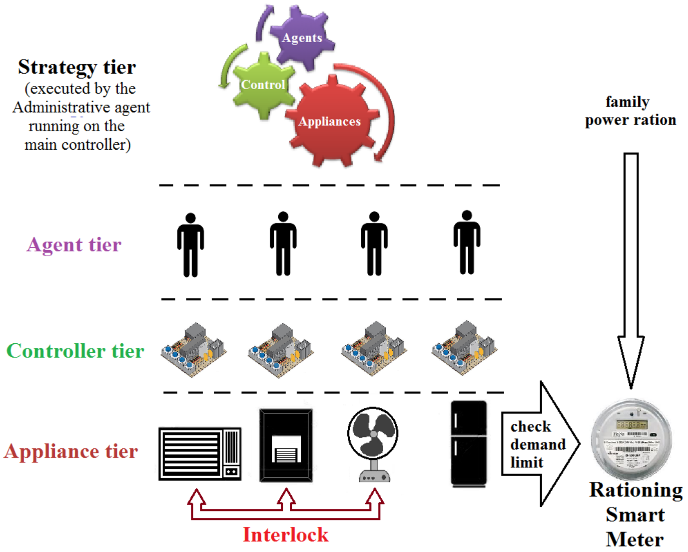

Figure 4.1: Four tier cyclic blackout mitigation strategy.

4.4 System Hardware

Interacting with people and trying to change their pattern of consuming power which, in the majority of cases, disturbs their daily routine directly and must be approached with caution. An unbalanced scenario doesn't take into consideration customers, their wellbeing and comfort could result in a strong reluctance to participate and co-operate. Further, over-reliance on people to perform solution-related activities could create confusion and chaos due to human error and misunderstanding, caused by inadequate training or inappropriate assumptions. Against this backdrop, designers minimise customer intervention with systems by embedding automation and adaptation. Thus the proposed system is designed to pay attention to such concerns, despite the fact that the problem is highly distributed, has a high degree of heterogeneity since it includes harnessing power from different and unrelated groups of generators and using the latter to power a population of heterogeneous appliances distributed over the targeted residential area.

The proposed infrastructure (Figure 4.2) consists of a Main System Controller (MSC), hosted at the local substation, responsible for orchestrating all parts of the system. It comprises a group of underutilised standby generators participating in covering the demand in addition to providing power to their owners (companies, hospitals, and workshops) located at their own premises around and within the targeted residential area. Each generator is equipped with a Generator Interfacing Controller (GIC) which has the responsibility of transferring the generator’s status information to the main controller. The next layer of the system is a group of House Local Controllers (HLC) distributed amongst dwellings on a one per house basic and used to control all related power consumption. The HLC is connected to the HVAC appliances in each house (ACs, COs, and MFs) and has the ability to measure ambient temperature and humidity. However this responsibility can be delegated to the customer. All controllers are connected wirelessly to secure various data and command transactions. Finally, the last part in the system is an energy storage device used to store unallocated power for other purposes such as street lighting during grid OFF periods at night and charging small electric vehicles such as motorcycles[54].

The system is also connected to the utility SCADA infrastructure for co-ordination and to receive cyclic blackout daily ON/OFF outage schedules. This connection is executed through a Utility Interface Controller (UIC) responsible for controlling the exchange of status information between the MSC and the main SCADA system. In addition, all dwellings are equipped with RSMs connected wirelessly to the MSC; RSMs are connected to the HLC for information and command exchanges.

RSM are accessible to customers through an interactive user interface and to the utility through its normal channel. The MSC is under the supervision of a human

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[54] During the field survey, it was found that certain types of electric motorcycles are starting to penetrate the commercial markets in Basra and have proven their suitability for use as a transport vehicle. These motorcycles have small battery packs that drive them throughout the course of their use. Charging from stored unallocated power is optional i.e. whenever there is sufficient stored energy in the battery. These batteries are neither intended to be used as storage devices for grid support operations nor intended to be used for supporting the operation of the proposed system (despite the fact that this is planned to be done in the next stage of this project). The field survey indicates that the majority of the batteries used in such electric motorcycles e.g. the Zhejiang Luyuan MY-BS4820-Z1 are 48V 20-38AH) requiring a 3 hrs-8 hrs charging time; such motorcycles typically consumes 600 W while running.

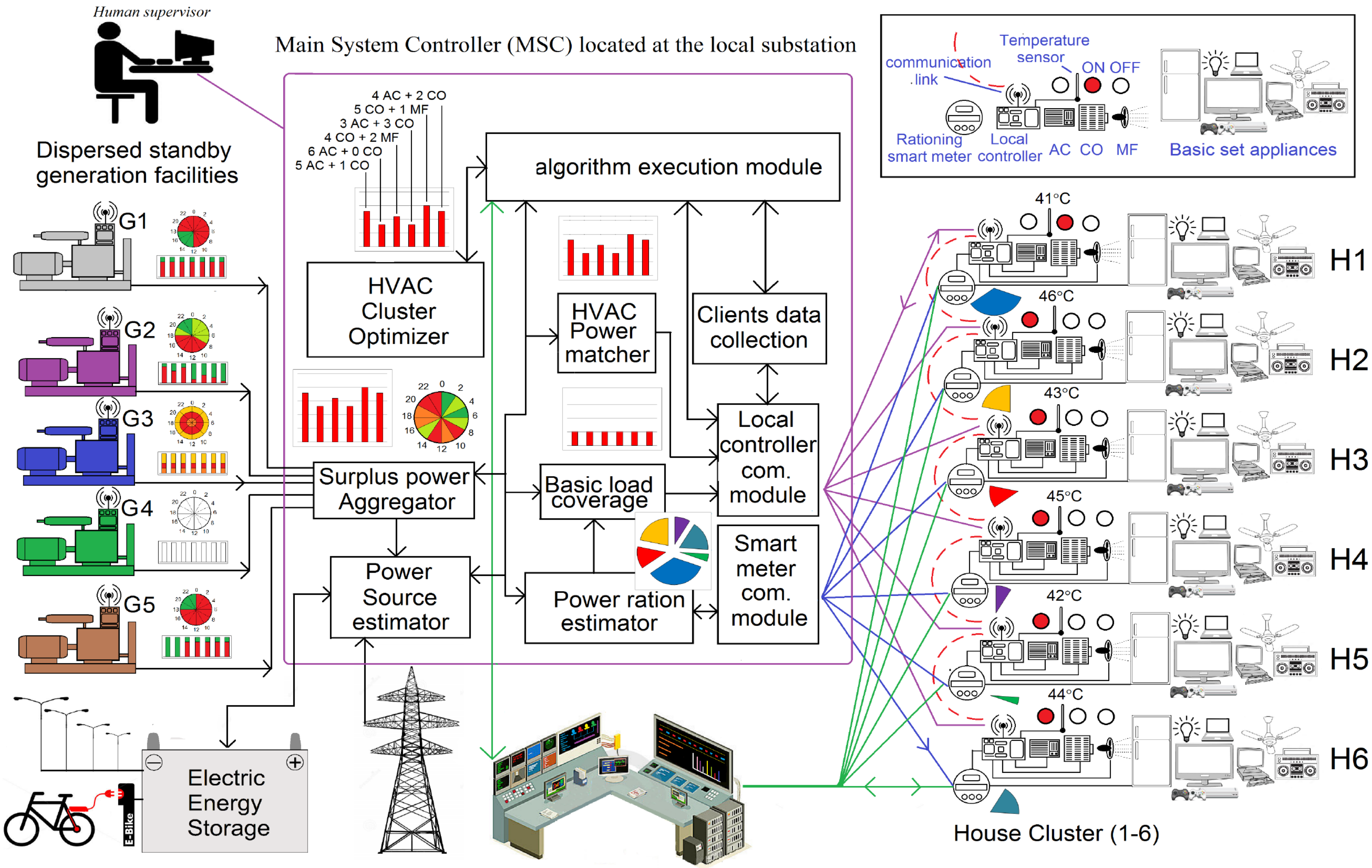

Figure 4.2: The proposed computer-controlled system.

operator. The figure at its centre provides an introductory description of main activities (covered in more details in the following sections).

4.5 The Underlying Assumptions

The proposed solution is based on a number of assumptions:

1. at least one standby generation facility in the vicinity of the targeted residential area willing to donate its surplus power[55].
2. the total surplus power of the available standby generation should not be less than the total power needed to power the basic set load plus one HVAC in all houses.[56]
3. each family defines its basic set of appliances; power-hungry appliances such as hair dryers and irons are not permitted. There is the freedom to have more than one type of basic set appliances e.g. more than one fridge or TV, as long as there is more than one family in a dwelling
4. each household should have at least an AC, a CO, and an MF
5. ACs' thermostats are assumed to be set to their minimum, justifiable for two reasons. Firstly, households normally set the AC thermostat to its minimum due to hot weather, cheap power prices, and the non-insulated, concrete-based housing builds. Secondly, it allows the solution to evaluate the impact of interlocking more than one AC in the same house.
6. the distribution of the allocated snooped power is executed over the LVDN
7. the connection, disconnection, measurement, protection infrastructure such as relays, circuit breakers, measurement devices integral to the solution are

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[55] Since all the targeted standby generation is owned by Government, it donated free of charge.

[56] Such an assumption can be justified since the basic appliance set is composed only of a minimum number of lights and fans, a TV, and a fridge in addition to one HVAC appliance. Provisioning power for this restricted mix for a typical Iraqi residential quarter as big as Kafaat, which contains ~500 houses, is possible especially when there is a significant level of surplus standby generation capabilities around the quarter e.g. South Oil Company alone has a 10 MW standby generation facility.

installed on the LVDN by participating authorities as needed.[57]

8. protection issues that could arise from the implementation of the solution are considered to be resolved by the participating authorities.
9. although the proposed hardware suggests dedicated wireless communication, any wired alternatives are acceptable.
10. the communication network is secure; no threat exists that could jeopardise the integrity of the data transferred
11. all power allocation and re-allocation decisions taken by house agents are accepted by customers.

4.6 System Agents

In the proposed system, the nature of the problem naturally favours a distributed solution, reflected in the proposed hardware. Following the same principle, agents are qualified software entities to administer the system through agent specific activities such as inter-agent negotiation and distributed decision making.

The proposed system comprises four types of controllers; MSC, GIC, HCL, and UIC and each hosts its own agent. The four agent types, in the same sequence as their host controllers, are the Administrative Agent (AA), the Generation Agent (GA), the House Agent (HA), and the Utility Agent (UA). All agents are designed to be 'reactive agents' also referred to as 'behavioural' or 'situated' agents [163]. They are 'Behavioural' due to the fact that overall system behaviour is defined by the aggregation of the individual behaviour components of its agents. The overall system performance evolves from aggregating the inter-agent behaviours taking into consideration the effects and limits of their temporal and spatial parameters imposed by the attributes of their environment. They are also 'situated' in the sense that these agents operate in an environment that reshapes their behaviour; here, the residential area with all dwellings, generation facilities, and distribution entities

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[57] Local and Central Government are willing to finance any promising solution targeting at mitigating the negative impact of chronic power shortages. Details of such protection schemes are given in Section 9.3.

is the environment. Not all agents have the authority to access and interact with the environment or all entities in it; they can be assigned influence zones over which they exercise full authority. Figure 4.3 shows agents, their environment, and their influence zones; the influence zones are the standby generation facilities for GAs, the local substation for UA, and all houses for HAs. Only the AA is capable of accessing all zones.

In general, reactive agents have task-specific modules based on the stimuli-response principle where certain stimuli from other agents, such as a request or in response to certain environmental changes such as an obstacle in front of an intelligent robot, can trigger a pre-programed reaction. The failure of a certain module in a reactive agent has no effect on other modules. Such flexibility creates a high level of fault tolerance.

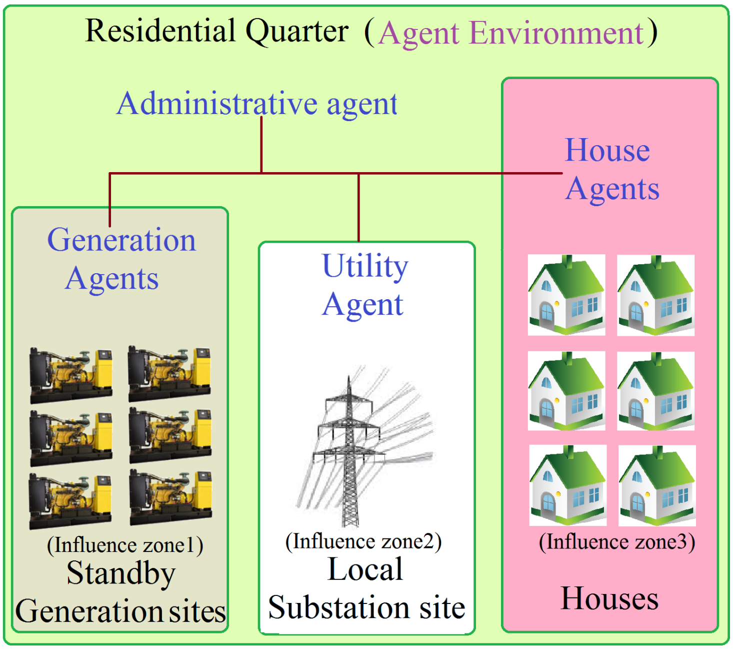

Figure 4.3: Agents and their environment showing influence zones.

The general architecture of reactive agents is based on the '*task accomplishing behaviour*' [218] in which a main task is divided into a series of sub-tasks with a certain module inside one or more agents dedicated for its execution. In this way each module can be considered as a '*finite-state machine*'. Agents working in this way are powerful entities in the sense that their behaviour is intelligent (because it responds in a logical way to various stimuli), consistent (because it follows a sequence of predefined states), and easy to debug (due to the predefined nature of the overall process).

4.6.1 The Generic Agent Architecture

Agents play an important role in distributed systems and their architecture reflects the requirements that must be satisfied. The architecture ultimately impacts overall system performance.

Several researchers have suggested reactive agent architectures for various applications. [219] suggest an agent structure composed of four blocks: decision, knowledge base, communication, and action with the aim of building an agent-based micro-grid. [181] suggest a reactive agent composed of the same blocks but added two new modules; data collection and knowledge update[58] in attempts to provide DSM within the smart grid.

Alternatively, [220] extend the design of his reactive agent to include other activities such as goal, action, reaction, negotiation, and sensor modules, as well as separating the decision making block into a local planning component and a plan database, using the latter to store all the rules used by the agent to interact with his environment and other agents. Old modules were segmented as in the case of the knowledge base into static and dynamic; the former was used to store non-updatable information, while the latter is used to store data which needed to be updated regularly. Four different modules in the design contain decision making information; plan, goal, and two knowledge bases (static and dynamic).

In the research, all the recruited agents are reactive software agents and the general architecture consists of nine major modules (Figure 4.4). Different agents are derived executing some or all of these system functions depending on the nature of the task they are recruited to achieve:

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[58] This module was added to the reactive agent design but not actually implemented.

1. **Decision Making Module:** a key module crucial to all agents considered to be the central module around which all other modules are clustered. It represents the main decision making entity and all other modules execute their tasks upon its request. In addition, all system operator interactions are carried out through this module.
2. **Communication Module:** responsible for inter-agent communication maintaining links between agents through sending/receiving command and data packets.
3. **Environmental Sensing Module:** responsible for gathering environmental parameters in order to furnish the agent with the ability to assess its environment. Parameters such as ambient temperature and humidity are typical frequently sensed values.
4. **Static Knowledge Base (SKB):** holds static information throughout the course of agent activity such as constant attributes and all fixed rules.
5. **Dynamic Knowledge Base (DKB):** holds information needed to be updated throughout the course of execution of the agent such as ambient temperature and humidity.
6. **Dynamic Knowledge Update Module:** responsible for updating the information stored in the DKB whenever there is a necessity to do so. The module has neither authority nor capability to change the information stored in the SKB.
7. **Action Execution Module:** responsible for performing certain actions such as turning appliances ON and OFF under the full control of the decision making module.
8. **Reaction Module:** responsible for all major activities performed by the agent depending on its category e.g. HAs are focused on house demand related activities.
9. **Negotiation Module:** responsible for performing all inter-agent negotiations under the supervision of the decision making module.

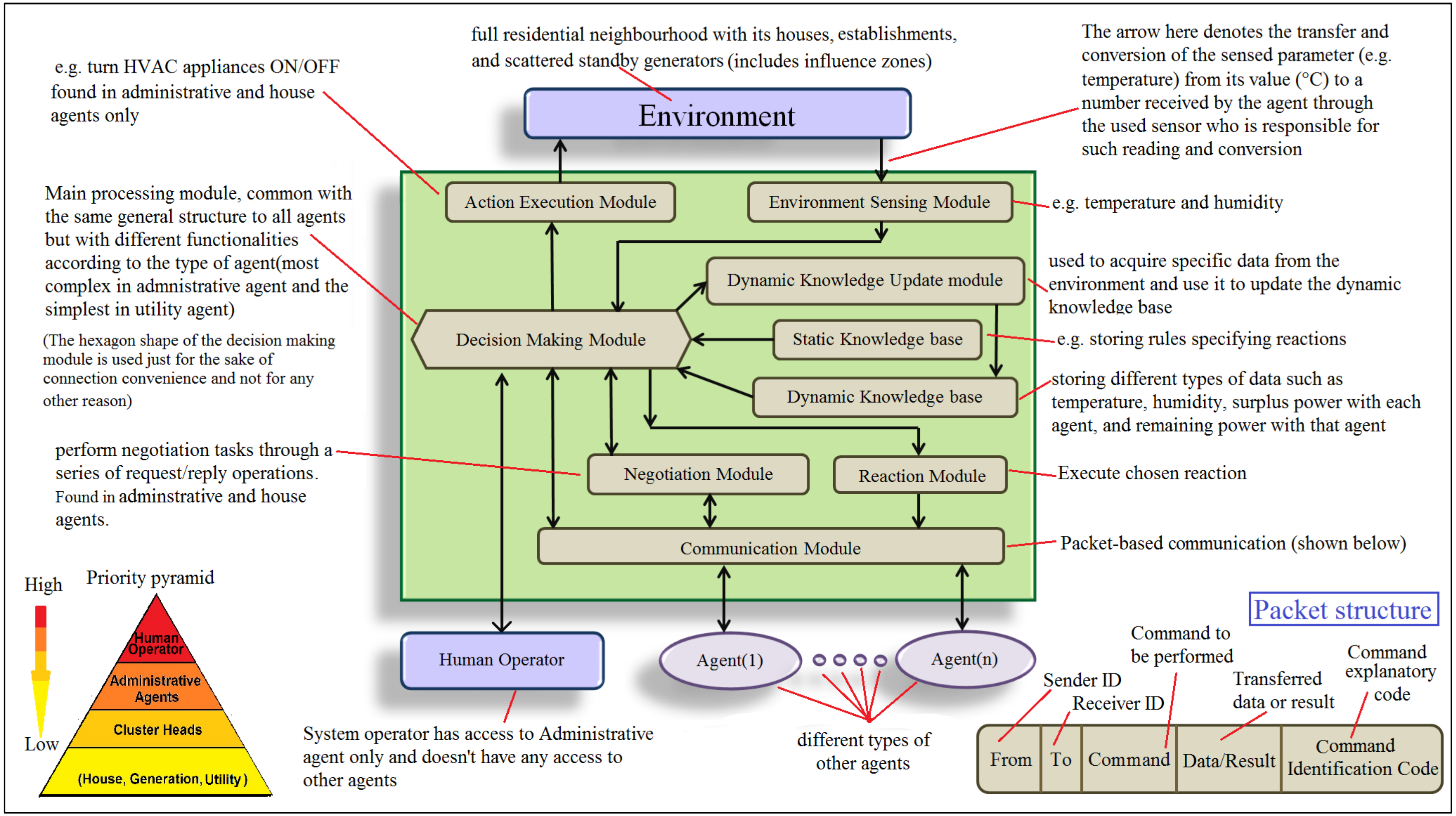

Figure 4.4: generic reactive agent architecture.

Table 4.1 shows a comparison between different agent architectures, highlighting the comprehensiveness of the architecture.

Table 4.1: A summary of the components of main agent architectures.

Module Given Name	**Decision making**	**Local Planning Module**	**General Knowledge Base**	**Static Knowledge Base**	**Dynamic Knowledge Base**	**Plan Module**	**Goal Module**	**Knowledge Update**	**Action Module**	**Reaction Module**	**Negotiation Module**	**Sensor Module**	**Data Collection**	**Communication Module**
Avramescu [219]	×		×						×					×
Logenthiran [181]	×		×					×	×				×	×
Wang [220]		×		×	×	×	×		×	×	×	×		×
This research	×			×	×			×	×	×	×	×		×
Module Category	Processing		Knowledge Archiving					Action				sensing		Commun.

4.6.2 The Derived Agents

Five types of agents are used to execute all system tasks arranged in a hierarchical layered structure according to their authority, duties, and responsibilities; these agents are hosted in the appropriate controllers:

1. **The Administrative Agent:** responsible for system startup at the beginning, orchestrating all operations, and initiating all sequences. It is hosted in the MSC located at the local substation; it communicates with all other agents through available networks. The AA is the only agent that can receive commands from the system operator.
2. **The House Agent:** hosted in the HLC, it is responsible for managing the demand of a single house through setting, checking and changing that demand through various ON/OFF operations for the targeted appliances.

The HA is also responsible for monitoring the ambient temperature and humidity inside the house, negotiating with other HAs for surplus power. It cannot receive commands from the operator directly.

3. **The Generation Agent:** hosted in the GIC, it is responsible for forwarding the information of a certain generator to the AA upon request such as operating hours and the amount of surplus power available. It comprises all the modules of the generic reactive agent except for action and negotiation modules and cannot contact the system operator directly. GAs do not control the generator they are interfacing to, since all generators are under the full control of their owners.
4. **The Utility Agent:** hosted in the UIC, it is dedicated to monitor the grid power supply schedule and provide it to the AA upon request. It comprises all the modules in the generic reactive agent without the negotiation and action, and also has no direct communication with the system operator. Only one UA is recruited in the proposed system.
5. **Cluster Heads (CHs):** members of HA and GA agents receiving commands and requests from the AA and distribute those tasks to fellow agents in the vicinity of its responsibility and vice versa, i.e. receiving commands from the AA and gathering responses from its cluster members and forwarding them back to the AA. The main role of CHs is the reduction of the communication burden from the AA. Houses are naturally grouped in clusters as are generators.

Table 4.2 shows a comparison of the basic four agent types (excluding cluster head agent) with a generic one as described earlier.

Table 4.2: A comparison of agent types.

Agent type	System operator access	Decision making	Communication Module	Environmental sensing module	Static Knowledge Base	Dynamic Knowledge	Dynamic knowledge update module	Action execution module	Reaction module	Negotiation module
Generic	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Administrative	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
House		✓	✓	✓	✓	✓	✓	✓	✓	✓
Generation		✓	✓	☑[59]	✓	✓	✓		✓	
Utility		✓	✓	☑[60]	✓	✓	✓		✓	

4.6.3 Agent Communications

One of the features distinguishing agents from other problem solving methods is their distribution, collaboration, and autonomous behaviour, which would be not possible without the ability to communicate with each other. The agent team uses a packet-based communication scheme verified by a request-acknowledgement-reply-acknowledgement handshake mechanism. The structure of the packet is shown in Figure 4.5 comprising a sender identification code, a similar one for the receiver (includes a ‘broadcast code’ which enables an agent to broadcast to all agents), a command code which describes in general what the sender wants from the receiver (there are seven general commands which are shown in Table 4.3), a payload field hosting results or any other requested data such as temperature, humidity, and finally a fifth field hosting the Command Identification Codes (CICs) used to explain, in more detail, the purpose of the command (field 3) and the required information. The CICs have positive implications on programming the

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[59] Module is available but currently disabled.

[60] Module is available but currently disabled.

agent leading to a more modular and easy to debug code. There are 41 dedicated CICs that can be used.

From	To	Command	Data/Result	Command ID Code

Figure 4.5: Inter-agent communication packet structure.

Table 4.3: Agent communication commands.

No.	Command	Description
1	NOP	No operation
2	Authorize	Authorize an agent to start a major task
3	Request	Request data from an agent
4	Reply	Send the requested data to that agent
5	Negotiate	Start negotiation with other agents about something
6	Inform	Announce something to one or more agent
7	Initialize	Start a minor operation (within a major task)

The packet is kept intentionally short, which has its advantages and disadvantages; short packets have the advantage of not wasting a lot of processing, transmitting, and receiving time, and no redundant or empty fields. On the other hand, long packets are efficient in transmitting long data burst but waste a lot of processing, transmission, and reception time if they are used to deal with small data payloads. Since the majority of the systems activities are commands and actions with no lengthy data transfer, short records are the optimum choice.

During the design stage of the system and its agent, it was assumed that the data and command transfer operations and communications are secure; thus there are no security measures (such as encryption and authentication) taken into consideration.

4.6.4 Agent Gaming

Games are important human activities that have evolved since the early stages of civilisation. Abstract competition is also attractive in artificial intelligence and since the state of the game during its various stages can be described easily, it offers an opportunity to apply agents as they can be assigned the ability to play the game fairly through the a well-defined set of commands [221]. Inter-agent negotiation plays an important role in these scenarios.

Activities such as resource sharing require agents to negotiate with each other in their quest to find a solution satisfying a need. Negotiation is based on "command – request – reply" packet exchanges between agents of the same category such as HAs and agents of different categories such as HAs and the AA. Thus, verifying this activity is important since it forms the foundation for a range of other actions. The agents' ability to negotiate effectively is validated by creating a test agent society composed of ten non-specialised generic reactive agents and tasking them to play a traditional number guessing game 'hangman', recording their activities throughout the game. In the game one agent generates a random number and the duty of other agents is to guess it through a series of request-reply operations. The agent activity chart of these agents is shown in Figure 4.6.

As illustrated, all agents have achieved their goal and have guessed the 'hidden' number successfully with different number of tries manifest in the width of the activity dark blue ribbon in front of the agent name. Guessing agents have long activity ribbons, since they are negotiating with all other agents (except themselves). From this game, it can be concluded that the proposed agents have the ability to communicate (and thus negotiating) successfully with each other, perform successful decision making tasks, and reach correct results.

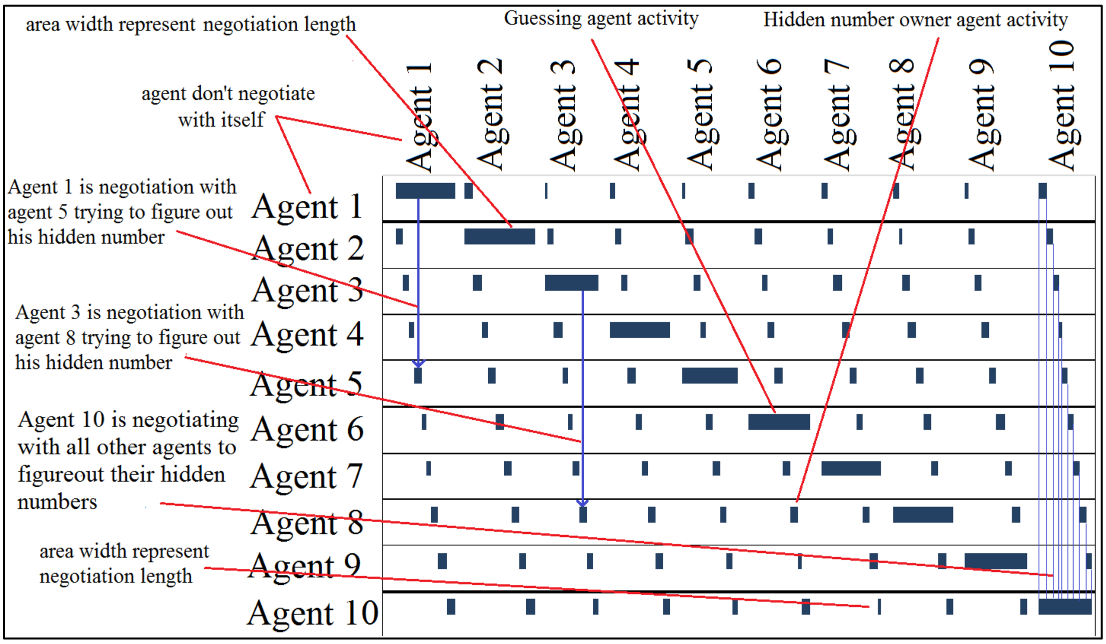


Figure 4.6: Agent activity chart during game playing activity.

4.7 The Demand Management Strategy

The aim of this solution is to mitigate the effects of cyclic blackouts in hot geographies without substantial investments in new generation installation and at the same time sustain basic household appliances and provide the best possible level of air conditioning/cooling without interfering with the grid power and its timings and supplied power; yet it must be fair in the manner it distributes available power amongst the dwellings of the targeted residential area.

In a fully-equipped healthy power system, power production and consumption can be represented by equation (4.1) which states that the supply consists of:

$$\overbrace{\left(\left.\underbrace{\left(\underbrace{\sum_{gu=1}^{Ngu}\sum_{gn=1}^{Ngn}P_{gu,gn}^{ugen}}_{Generation}-\underbrace{\sum_{\mathrm{ur}=1}^{Nures}P_{ur}^{ures}}_{Reserve}-\underbrace{\sum_{tl=1}^{Ntl}P_{tl}^{txloss}}_{Transm.\ Losses}-\underbrace{\sum_{dl=1}^{Ndl}P_{dl}^{dxloss}}_{Distribution\ losses}\right)}_{Grid}\right|_{P^{grid}>0}+\left.\underbrace{\left(\underbrace{\sum_{gs=1}^{Ngs}\sum_{lo=1}^{Nlo}P_{gs,lo}^{sb}}_{Generation}-\underbrace{\sum_{\mathrm{sr}=1}^{Nsbres}P_{sr}^{sbres}}_{Reserve}\right)}_{Standby}\right|_{P^{grid}=0}\right)}^{Supply}\geq$$

$$\overbrace{\left(\underbrace{\sum_{dce=1}^{Ndce}\sum_{ap=1}^{Nap}P_{dce,ap}^{cust}}_{All}\right)}^{Demand}\ldots\ldots\ldots\ldots\ldots\ldots \tag{4.1}$$

Where:

N : Total number of houses
Ngs : Standby generation facility
Nlo : Number of local standby generators in the same facility
P^{sb} : Standby power
P^{grid} : Grid power
Ngu : Number of utility generation plants
Ngn : Number of generators in the targeted power plant
P^{ugen} : Utility power
Ntl : Number of locations having transmission losses

P^{txloss} : Transmission system power losses
Ndce : Number of Demand Consuming Entity (e.g. house)
Nap : Number of Electric appliance, device, or instrument
P^{cust} : Customer demand
Ndl : Number of locations having distribution losses
P^{dxloss} : Distribution system power losses
Nures : Number of utility reserves
P^{ures} : Utility reserve
Nsbres : Number of available standby reserves
P^{sbres} : Standby generation reserve

In case of a cyclic blackout and during the OFF period, the power equilibrium relationship of Equation 4.1 becomes:

$$\left(\underbrace{\underbrace{\sum_{gs=1}^{Ngs}\sum_{lo=1}^{Nlo} P_{gs,lo}^{sb}}_{Generation} - \underbrace{\sum_{sr=1}^{Nsbres} P_{sr}^{sbres}}_{Reserve}}_{Standby}\right) \geq \left(\underbrace{\overbrace{\sum_{dce=1}^{Ndce}\sum_{ap=1}^{Nap} P_{dce,ap}^{cust}}^{Demand}}_{Covered\ by\ sbtandby}\right) \dots\dots\dots (4.2)$$

For $t=1,2,3,\dots,T_{\mathbf{Blackout}}$
$\tau_{\mathbf{min}} \leq \tau \leq \tau_{\mathbf{max}}$
$h_{\mathbf{min}} \leq h \leq h_{\mathbf{max}}$

Replacing demand by its true consuming components Equation (4-2) becomes:

$$\left(\underbrace{\underbrace{\sum_{gs=1}^{Ngs}\sum_{lo=1}^{Nlo} P_{gs,lo}^{sb}}_{Generation} - \underbrace{\sum_{sr=1}^{Nsbres} P_{sr}^{sbres}}_{Reserve}}_{Standby}\right) \geq \left(\underbrace{\underbrace{\overbrace{\left.\sum_{dce=1}^{Ndce}\sum_{ap=1}^{Nap} (Na_{dce,ap} * Pa_{dce,ap} * Ca_{dce,ap})\right]_{t,\tau,h}}^{Demand}}_{Ca=Ca_{off}\text{ or }Ca_{partial}\text{ or }Ca_{on}}}_{Covered\ by\ Standby\ power}\right) \dots\dots\dots (4.3)$$

For $t=1,2,3,\dots,T_{\mathbf{Blackout}}$
$\tau_{\mathbf{min}} \leq \tau \leq \tau_{\mathbf{max}}$
$h_{\mathbf{min}} \leq h \leq h_{\mathbf{max}}$

where

$Na_{a,h}$: Number of appliance of type (a) in a house (h).
$Pa_{a,h}$: Power of the specified appliance (a) in house (h)
$Ca_{a,h}$: Final aggregated control actions that are applied to the appliance in order to control its power consumption. These actions include:

Ca_{on} : turning the appliance ON at full power, Co_{on} = 1.
Ca_{off} : turning the appliance OFF, Co_{off} = 0.
$Ca_{partial}$: operating the appliance at partial power, i.e. $Ca_{off} < Ca_{partial} < Ca_{on}$ and it is appliance Dependent (as in the case of using dimmers).

t : Blackout time slot number ($t=1,2,3,\dots,T_{\mathbf{Blackout}}$)
τ : Ambient temperature ($\tau_{\mathbf{min}} \leq \tau \leq \tau_{\mathbf{max}}$)
h : Ambient humidity ($h_{\mathbf{min}} \leq h \leq h_{\mathbf{max}}$)

4.7.1 Grouping of Standby Generation

The demand management strategy relies on mapping all standby generation facilities identifying any surplus power, aggregating all this power, and allocating this power to every house according to a certain 'fair' criterion that enables an acceptable level of comfort. For the purposes of the research, four types of standby generators are recognised (Table 4.4):

1. **Public Standby:** owned by the local government, provide power free of charge and are of a continuous type. For the purpose of the project they are considered to be the main standby sources of power during Grid OFF periods. The local government covers all the fuel and running costs for these units.
2. **High Priority Standby:** owned normally by a public hospital or medical facility but does not include private hospitals which are treated as any other private establishment. These generators are also of a continuous type and the local government covers all fuel and running costs.
3. **Commercial Standby:** installed to provide power during grid OFF periods for a pre-defined monthly fee. These generators are also of a continuous type and are considered only in the case of providing extra power to participating customers beyond their share in exchange for a fee e.g. for operating more ACs. The local government, in an attempt to limit the cost to the customer, provides fuel at reduced price and pays half the running costs for these units during July and August each year.
4. **Domestic Standby:** most households have their own standby generators run on gasoline or diesel; some are sufficiently large to supply a level of power to neighbours. Domestic generators are not an attractive choice in terms of the proposed solution owing to noise, pollution, and high running costs.

For the purposes of the project, the hierarchy of standby power starts from public generators through commercial units to finally from domestic resources, considered as the last resort.

Table 4.4: Standby generation types and their main attributes.

Type of Standby generation	**Cost coverage by local government**	**Operating mode**	**Ownership**	**Fuel type**	**Usage priority (1-4)**
Public	Full	Continuous	Government	Diesel	1
Critical	Full	Continuous	Government	Diesel	2
Commercial	Reduced fuel + half operational cost	Continuous	Commercial	Diesel	3
Domestic	No	Mixed	private	Mixed	4

According to this standby generation taxonomy, the left-hand side of Equation 4.3 can be expanded to cover these four types of standby generators as:

$$\sum_{gs=1}^{Ngs}\sum_{lo=1}^{Nlo} P_{gs,lo}^{sb} = \underbrace{\underbrace{\sum_{p=1}^{Ngp} P_p^{pub}}_{\substack{Main\ Power\\ Source}} + \underbrace{\sum_{r=1}^{Ngr} P_r^{cri} + \sum_{c=1}^{Ngc} P_c^{com} + \sum_{d=1}^{Ngd} P_d^{dom}}_{Reserve}}_{Standby} \quad \ldots (4.4)$$

where

Ngp : Total number of public standby generators
Ngr : Total number of high priority standby generators
Ngc : Total number of commercial standby generators
Ngd : Total number of commercial standby generators
P^{pub} : Power generated by public generator number
P^{cri} : Power generated by critical generator number
P^{com} : Power generated by commercial generator number
P^{dom} : Power generated by domestic generator number

The above equation includes implicitly the standby reserve since some of the generation assets are considered as reserve for the rest. Substituting Equation 4.4 into Equation 4.3 yields:

$$\underbrace{\underbrace{\sum_{p=1}^{Ngp} P_p^{pub}}_{\substack{Main\ Power\\ Source}} + \underbrace{\sum_{r=1}^{Ngr} P_r^{cri} + \sum_{c=1}^{Ngc} P_c^{com} + \sum_{d=1}^{Ngd} P_d^{dom}}_{Reserve}}_{Standby} \geq \underbrace{\underbrace{\overbrace{\sum_{dce=1}^{Ndce}\sum_{ap=1}^{Nap}\left(Na_{dce,ap} * Pa_{dce,ap} * Ca_{dce,ap}\right)\Bigg]_{t,\tau,h}}^{Demand}}_{Ca=Ca_{off} \text{ or } Ca_{partial} \text{ or } Ca_{on}}}_{Covered\ by\ Standby\ power} \quad \ldots\ldots (4.5)$$

for t=1,2,3,…,$T_{\textbf{Blackout}}$
$\tau_{\textbf{min}} \leq \tau \leq \tau_{\textbf{max}}$
$h_{\textbf{min}} \leq h \leq h_{\textbf{max}}$

Equation 4.5 describes the power balance that should be reached, the aim of any strategy considering multiple streams of power collaborating to cover the demand of a population of different appliances through managing demand using appropriate control and management to match demand to the available supply, taking into consideration losses in LV distribution networks. Any surplus power remaining can be managed using other techniques such as storage. The amount of standby reserve depends on several factors such as the generator owner policy, effective regulations, type of connected loads and weather conditions.

4.7.2 Main System Concept

The main principle underpinning the proposed solution is a dual-mode, robust, power management system capable of providing the power needed to mitigate cyclic power blackouts and to prevent their onset by managing demand peaks. The backbone is a demand coverage strategy referred to as PANDA that has the ability to cover consumer demand in a prioritised fashion starting with the most essential loads whilst at the same time provisioning power to a minimum set of different demand HVACs fairly, on a one per family basis, using the aggregated surplus power from neighbouring standby generation facilities or any other sources. This eliminates the need to install new generation capabilities and shortens the implementation time of any solution.

The solution harnesses a collection of techniques, such as: power snooping from neighbouring generation facilities, agent utilisation, SDM, HVAC appliances adaptive clustering, HVAC appliances interlocking, demand negotiation between dwellings, power rationing, consumption monitoring and intervention. During its course of operation, PANDA must fulfil several constraints:

1. **Demand adaptability:** the total demand of all participating HVACs must not exceed the available snooped power.
2. **Demand diversity:** no restrictions on the demand of the HVAC appliances, as long as this is kept within practical limits.
3. **Service optimization:** the provision of the optimum air conditioning service

possible. In this context, ACs are superior to COs, which in turn are superior to MFs.

4. **Coverage scalability:** the HVAC cluster should be able to accommodate for all the HVAC appliances of any typical residential neighbourhood.
5. **Distribution Fairness:** all households enjoy the same total amount of HVAC usage time.
6. **Fairness prioritization:** fair distribution supersedes power usage efficiency.
7. **Power utilization:** all the surplus power must be either used or stored.
8. **Implementation flexibility:** the proposed system should give customers the freedom to define their basic set, can operate with any grid ON/OFF timings, doesn’t enforce any supply obligations on participating standby generation, and needs low investments.
9. **Supply controllability:** power consumption should be monitored and intercepted if a customer breaches his power ration.

Figure 4.7 shows the operating principle of PANDA.

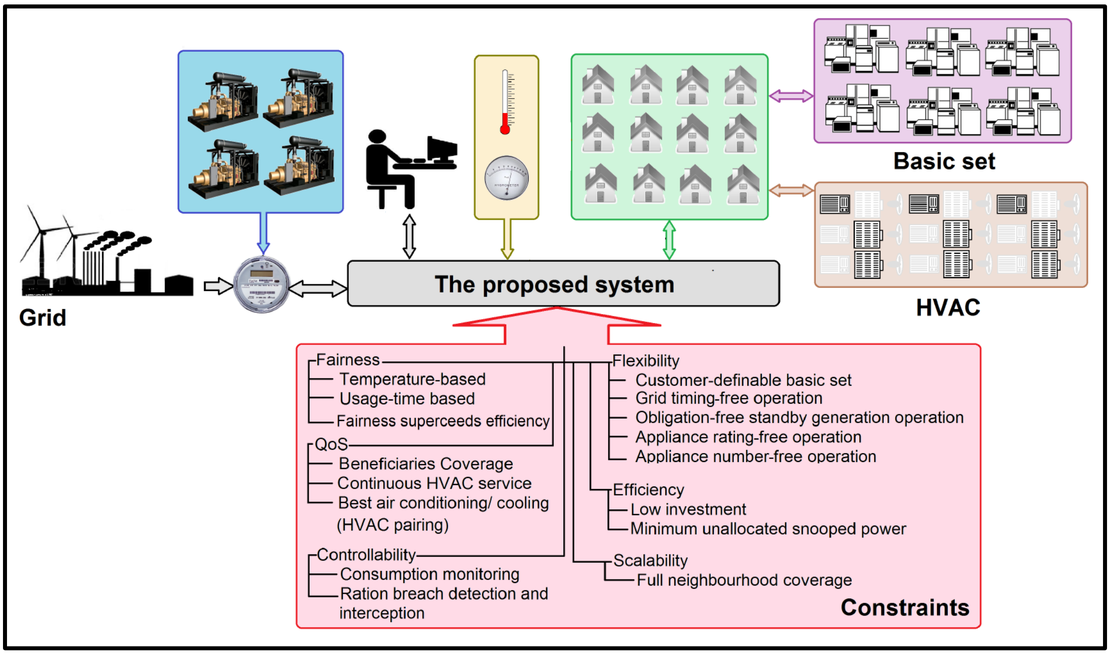


Figure 4.7: The principles of PANDA and operational conditions

The mitigation and demand containment strategy is implemented in multiple phases; firstly by aggregating all surplus power available from underutilised standby generation distributed around the targeted residential area. Power sources are categorized according to their availability, access authorisation, and operational cost, queued according to their affordability and used sequentially. Secondly, by determining the current power requirements, classification of the currently used appliances by their importance to the customer, their power consumption, and referenced to the demand to be covered. Thirdly, by grouping of the appliances into two fixed size clusters: the first is a static cluster hosting a fixed community of essential BS appliances that must be powered at all times, containing all appliances essential to maintaining daily life in its minimum acceptable form, and a second dynamic adaptive cluster hosting three different demand HVAC appliances for each family - an AC, a CO, and an MF interlocked together. Fourthly, all the demand of the basic set cluster covered from the power snooped from the standby generators and the remainder is used to cover the demand of a third of the HVAC cluster population by powering only one of the HVAC appliances per family. The type of HVAC appliance to be powered depends mainly on the available surplus power. The system allocates the HVAC appliances usage rights among all households in a fair way according to the ‘fair share’ and ‘temperature-triggered’ strategies. In the prevention mode, one of the ACs of each family is replaced by a CO and if this is not enough more ACs are turned OFF in order to manage the overall demand.

This mitigation and prevention strategy can be deployed in a range of power shortage scenarios whether periodic or non-periodic, scheduled or sudden, short or long cyclic blackouts. It also can be used in any demand management strategy whether initiated by the consumer, the power provider, or by a researcher in a simulated environment. This degree of flexibility is supported by the ability to process different data sources ranging from historical through to real-time data extracted from sensors and user interface devices. The diversity of data sources has widened its effectiveness in developing and evaluating power management strategies aimed at mitigating and preventing cyclic blackouts and managing power shortages.

The solution has the consumer essential needs as its main driver by provisioning demand side management measures and at the same time maintaining an acceptable level of comfort. The PANDA demand coverage strategy is most effective in extreme weather in areas plagued by severe power shortages.

4.7.3 The Demand Management Strategy

The proposed demand management strategy is founded by classifying four domestic demand types:

1. **Basic Set:** operated in order to support the minimum daily life requirements for any family. These appliances are family and community dependent but in general there is a common set that matches the basic needs comprising lights, fans, refrigerators, TV, satellite receiver, and laptops. Other appliances such as washing machines are not operated every day, and in cyclic blackout scenarios they can be shifted to the grid's power ON periods. Appliances with thermal storage, such as chest freezers, are not affected during short to moderate power OFF periods. More than one basic set appliances of the same type (such as TVs and refrigerators) can be allowed for households hosting more than one family.
2. **HVAC appliances:** crucial in hot countries and include ACs, COs, and MFs. During the hot season, they become all-day necessities.
3. **Power-hungry appliances:** consuming a significant level of power and are not an all-day necessity. Examples are hair dryers, irons, and tumble driers. In cyclic blackout scenarios, their usage can be shifted to the grid power ON periods.
4. **Shiftable appliances:** No urgent need for them thus they can be operated at grid power ON periods. They include washing machine, PC, Game council, stereo, blinder, and water pump.

Thus PANDA aims to provide power to customers for the first two classes during grid power OFF periods and shifts the usage of the third class to the power ON periods.

The required power is secured from aggregating surplus power from standby generators, which is then used to power all basic set appliances, and the remainder is used to power a subset of the HVAC cluster population. The level of surplus power designates a certain mix for the HVAC adaptive cluster. It is assumed that all the three types (or at least one at the minimum) are found in each dwelling. Thus, the HVAC cluster comprises three subsets, each a subset of the universal HVAC appliance set (*H*):

$$A^q = \{a_h^q : a_h^q \in H\}_{h=1}^{N} \dots\dots\dots\dots\dots\dots (4.6)$$

$$C^q = \{c_h^q : c_h^q \in H\}_{h=1}^{N} \dots\dots\dots\dots\dots\dots (4.7)$$

$$M^q = \{m_h^q : m_h^q \in H\}_{h=1}^{N} \dots\dots\dots\dots\dots (4.8)$$

where $A^q, C^q, and\ M^q$ are the sets hosting all HVAC appliances in that residential quarter. a^q , c^q , m^q are members of these sets, each located at house number (*h*) in a residential quarter (*q*) which has (*N*) houses, where (N) satisfies the “coverage scalability” condition (Section 4.7.2).

The HVAC adaptive cluster (O) consists of all of these three sets:

$$O = A^q \cup C^q \cup M^q \dots\dots\dots\dots\dots..(4.9)$$

From the generic sets (4.6, 4.7, and 4.8), only a subset of each type is powered at any period. Thus there are three subsets:

$$A^s \subseteq A^q \dots\dots\dots\dots\dots\dots (4.10)$$

$$C^s \subseteq C^q \dots\dots\dots\dots\dots\dots (4.11)$$

$$M^s \subseteq M^q \dots\dots\dots\dots.\dots (4.12)$$

The total number of powered HVAC appliances in these three sets must be equal to the number of houses in the residential quarter in order to fulfil the “coverage scalability” condition:

$$\#A^s + \#C^s + \#M^s = N \dots\dots\dots\dots\dots\dots (4.13)$$

The powered set of HVAC appliances (D) is defined as a subset of O and it should be one third its size:

$$\mathrm{D} \subset \mathrm{O} \mid \#\mathrm{D} = \#\mathrm{O}/3 \dots\dots\dots\dots\dots\dots (4.14)$$

Furthermore, there is no situation exists in which all the three HVAC subsets are powered at any moment of time:

$$\nexists \mathrm{D} \subseteq \mathrm{A^s} \cup \mathrm{C^s} \cup \mathrm{M^s} \leftrightarrow (\mathrm{A^s} \neq \emptyset, \mathrm{C^s} \neq \emptyset, \mathrm{M^s} \neq \emptyset) \dots\dots\dots\dots\dots\dots (4.15)$$

On the other hand, the total power required to operate each subset ($\mathrm{p^{at}}, \mathrm{p^{ct}}, and\ \mathrm{p^{mt}}$) is determined by its size which is in turn is calculated depending on the amount of the available surplus power ($\mathrm{P^{sn}}$), thus:

$$\mathrm{p^{sn}} = \sum_{\mathrm{s}=1}^{\mathrm{G}} \mathrm{p_s^{sn}} \dots\dots\dots\dots\dots\dots (4.16)$$

and

$$\mathrm{p^{at}} = \sum_{\mathrm{h}=1}^{\mathrm{N}} \mathrm{p_h^a} \dots\dots\dots\dots\dots\dots (4.17)$$

$$\mathrm{p^{ct}} = \sum_{\mathrm{h}=1}^{\mathrm{N}} \mathrm{p_h^c} \dots\dots\dots\dots\dots\dots (4.18)$$

$$\mathrm{p^{mt}} = \sum_{\mathrm{h}=1}^{\mathrm{N}} \mathrm{p_h^m} \dots\dots\dots\dots\dots\dots (4.19)$$

where $\mathrm{p_s^{sn}}$ is the surplus power from generator (s) and ($\mathrm{p_h^x}$) is the power consumed by a HVAC appliance of type (x) located at house (h).

If the surplus power is sufficient to power all ACs on a one per household basis then D is defined as:

$$\mathrm{D{=}A^{q}} \leftrightarrow (\mathrm{p^{sn}} \geq \mathrm{p^{at}}) \ldots \ldots \ldots \ldots \ldots \ldots (4.20)$$

Otherwise if the power is only sufficient to power a collection of ACs and COs then D can be defined as:

$$\mathrm{D} \subset \mathrm{A^{s}} \cup \mathrm{C^{s}} \leftrightarrow (\max(\#\mathrm{A^{s}}), \min(\#\mathrm{C^{s}}), (\#\mathrm{A^{s}} + \#\mathrm{C^{s}} = \mathrm{N}), \mathrm{p^{at}}{>}\mathrm{p^{sn}}{>}\mathrm{p^{ct}}) \ldots\ldots\ldots\ldots (4.21)$$

In the relationship, there are four conditions to be satisfied; the number of participating ACs must be maximized and the number of COs must be minimized in order to provide the best possible air conditioning/cooling service, the total number of powered ACs and COs must equal the number of houses, and finally the snooped power level must be less than the power needed to operate all ACs but at the same time more than the power needed to power all COs. If this is not the case and the power is barely sufficient to power all COs, then D is defined as:

$$\mathrm{D{=}C^{q}} \leftrightarrow (\mathrm{p^{sn}} = \mathrm{p^{ct}}) \ldots \ldots \ldots .. (4.22)$$

If the power level is less, a collection of COs and MFs are powered if the number of participating COs is maximized, the number of COs is minimized, the total number of powered COs and MFs is equal to the number of targeted houses, and finally the surplus power level is less than the power needed to operate all COs but at the same time it is more than the power needed to power all MFs. In this case D can be defined as:

$$\mathrm{D} \subset C^{s} \cup M^{s} \leftrightarrow (\max(\#C^{s}), \min(\#M^{s}), \#C^{s} + \#M^{s} = N, p^{ct}{>}p^{sn}{>}p^{mt}) \ldots.. (4.23)$$

If the power is even lower but still sufficient to power all MFs, then D equals:

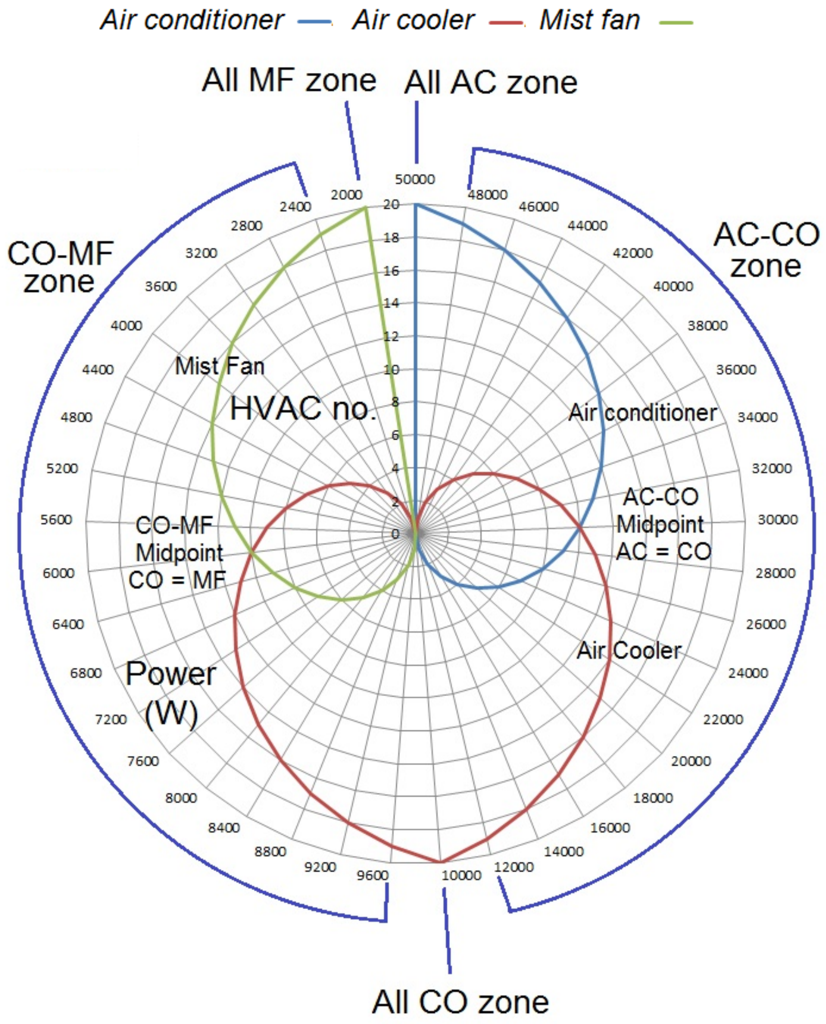
$$\mathrm{D{=}M^{q}} \leftrightarrow (\mathrm{p^{sn}} = \mathrm{p^{mt}}) \ldots\ldots\ldots. (4.24)$$

Ultimately the surplus power available is such that it is not possible to provide any air conditioning/cooling service and D is defined as:

$$D = \emptyset \leftrightarrow (p^{sn} < p^{mt}) \ldots\ldots\ldots\ldots\ldots\ldots (4.25)$$

The previous conditions collectively satisfy the “service optimization” and the “demand adaptability” conditions.

Figure 4.8 shows the relationship between a certain surplus power level and the mix of ‘all AC, ‘all CO’, and/or ‘all MF’ scenarios generated according to a certain AC, CO, and MF demand; other demands yield similar curves. Clustering of HVACs has been driven by a range of surplus power levels used for twenty houses.



For: Air Conditioner = 2500 W, Air Cooler = 500 W, Mist fan = 100 W

Figure 4.8: The composition of a HVAC cluster for 20 dwellings.

The total demand of a variable-size set of the three types of HVAC appliances (ACs, COs, and MFs) is plotted covering a range from 1 up to 20 appliance of each type (according to the maximum number of targeted households) in both (AC-CO) and (CO-MF) pairing schemes organized in two main groups; on the right representing the AC-CO pairing and the left representing the CO-MF pairing. Each of these two groups contains two graphs; drawing a beam from the centre of the available power level (on the circumference) and locating the intersection of this beam of the two demand graphs, reveals the optimum number of ACs and COs (in a AC-CO pairing) or CO-MF (in a CO-MF pairing) that can be powered by the specified level of surplus power. The same process is relevant to the other half of this graph.

The representation also helps to identify three specific cases; the first when amount of available surplus power is barely enough to power MFs only; the second is when the available power is sufficient to power only Cos; and finally, when the surplus power is sufficient to power all ACs, provisioning the optimum air conditioning possible.

The demand management strategy is designed as a three stage process:

Stage 1 - Basic Set Coverage (Phase 1 and Phase 2)

In this stage (Figure 4.9), the demand of basic set of appliances is covered through a two phase operation. The AA scans all GAs requesting their surplus power, their availability, and price (unit price/kWh) if applicable (as in the case of a commercial generator participating in the operation; other types e.g. public and hospital are assumed to be free). Upon the receipt of the information from GAs, the AA aggregates all individual generator schedules into a unified environment and determines the overall availability of the total surplus power. Figure 4.10 is a description of a daily schedule of the participating generators and shows an example of how the total surplus power is calculated considering a variety of real-life generator schedules, as identified during the field survey. Some generators have ON and OFF periods during the day, while others run continuously. Amongst the latter, some of them just run with continuous load, while others have different loads throughout the day.

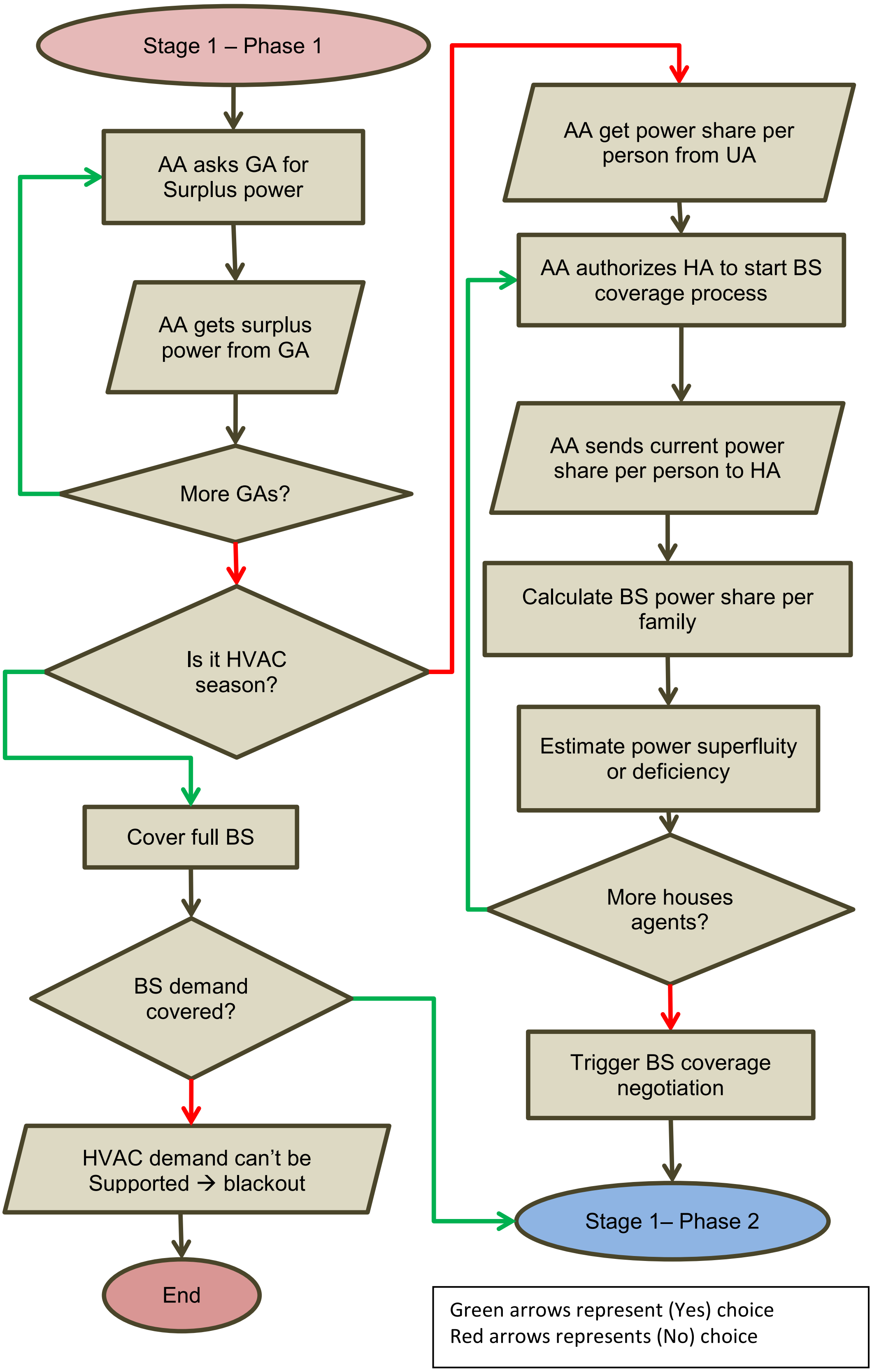
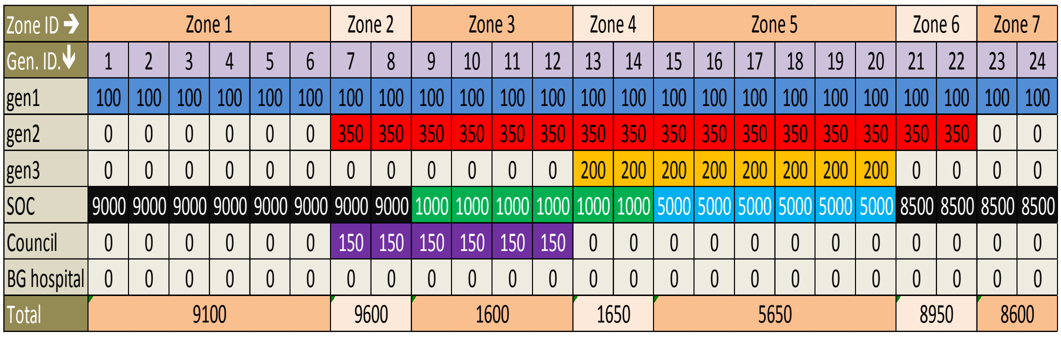


Figure 4.9: PANDA stage 1, phase 1 (basic set coverage).

The diversity in daily generation schedules leads to the formation of ‘time zones’ with consistent surplus power profiles i.e. continuous periods of time with the same overall power level. Figure 4.10 shows seven time zones of different durations. It is worth noting that hospital generators are ‘normally’ excluded from the overall snooped power, since they are viewed as strategic standby generation assets for the purposes of the overall system.



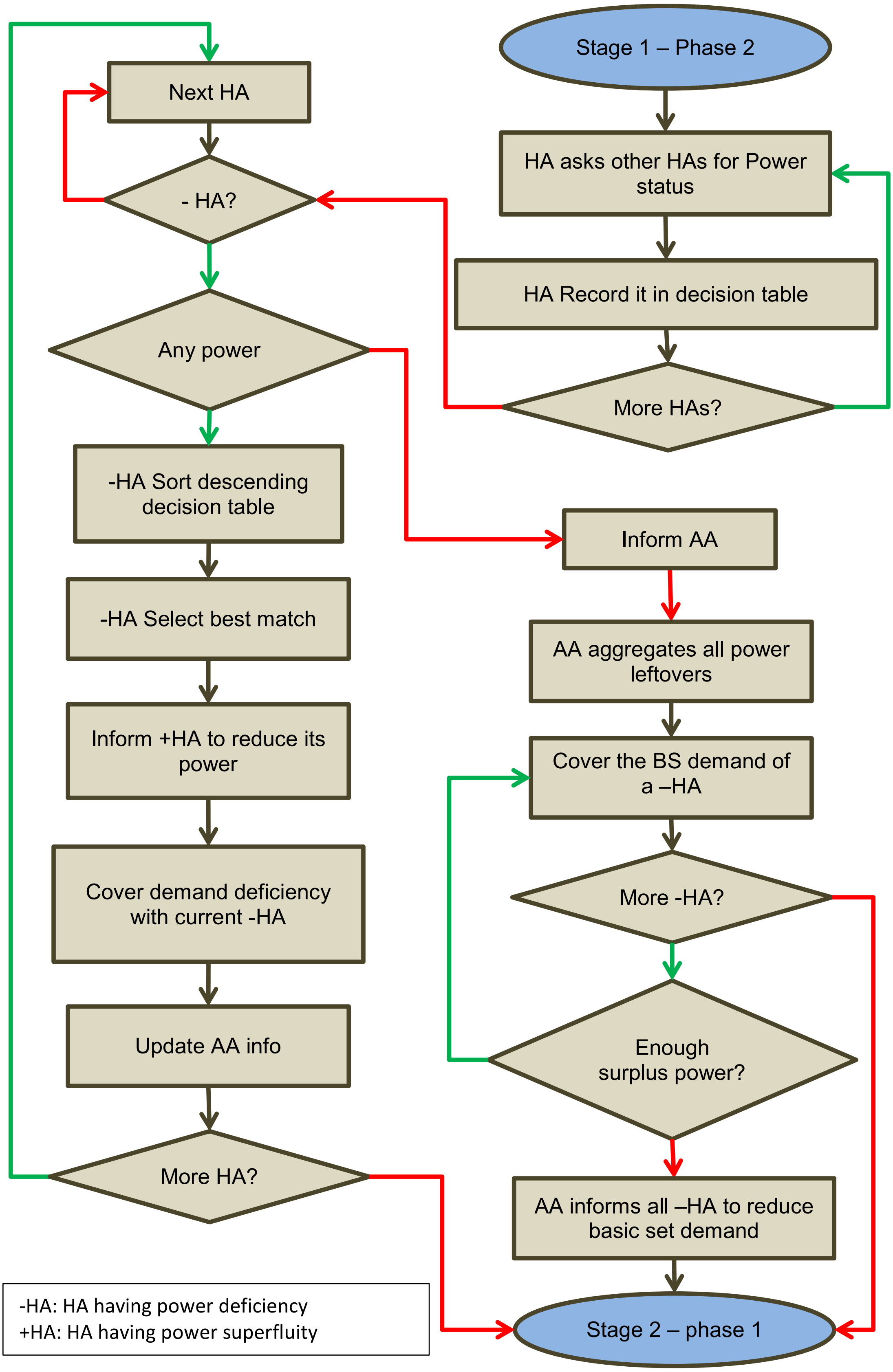
Zone ID →	Zone 1						Zone 2		Zone 3				Zone 4		Zone 5						Zone 6		Zone 7	
Gen. ID.↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
gen1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
gen2	0	0	0	0	0	0	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	0	0
gen3	0	0	0	0	0	0	0	0	0	0	0	0	200	200	200	200	200	200	200	200	0	0	0	0
SOC	9000	9000	9000	9000	9000	9000	9000	9000	1000	1000	1000	1000	1000	1000	5000	5000	5000	5000	5000	5000	8500	8500	8500	8500
Council	0	0	0	0	0	0	150	150	150	150	150	150	0	0	0	0	0	0	0	0	0	0	0	0
BG hospital	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	9100						9600		1600				1650		5650						8950		8600	

Figure 4.10: Surplus power aggregation.

In the next step, the AA determines the season, of critical importance due to its substantial impact on the electrical demand, especially in residential areas. Summer and winter periods are characterised by heavy HVAC demand; thus the solution must be able to manage demand allocation in response to these changes. During summer/winter all BS demand is met from surplus power since it represents a small fraction of overall demand which is dominated by HVAC usage. In spring/autumn BS is the only contributor to the overall demand and is thus covered entirely from the limited utility supply. In this case, a power share per person is issued and a family share can be estimated and used to power these BS appliances.

Thus during summer/winter all BS demand is covered from the power surplus from donor GAs; in spring/autumn, the grid provisions the agreed power share. In the latter scenario, of critical importance is that the local power management authorities define the share, based on accurate field surveys that assess the current population, the family of appliances and their usage patterns. Comparison of the power share with its BS demand reveals the magnitude of the power deficiency, if any. This process is repeated for all HAs.

HAs managing a power deficiency negotiate to secure power to meet their BS demand from other HAs enjoying a power surplus (Figure 4.11). Thus Phase 2 of the BS demand coverage operation is a mapping of HAs current power requirements i.e. whether they have a power surplus or deficit. The information is captured in a dedicated table, sorted in descending order according to the power available (ranking more substantial levels of surplus power higher and leaving the smaller, more flexible, to be allocated at the end). HAs seeking power interrogate the table entries searching for an agent that possesses the smallest amount of surplus power necessary to cover its demand shortage. The table is then updated accordingly. This process is repeated for all agents and each time, the AA is informed about the power transactions; any HA unable to meet demand issues a report to the AA. The AA aggregates all remaining power segments and allocates it to cover the demand of HAs still subject to a power shortage. If the aggregated power is not sufficient to cover the needs of a single agent, part of that need is covered and the remainder is managed through BS demand trimming.



-HA: HA having power deficiency
+HA: HA having power superfluity

Figure 4.11: Stage 1, Phase 2 of BS demand coverage negotiations.

Figure 4.12 is an inter-agent activity chart showing BS demand coverage negotiation, highlighting HA authorisation (AA authorise HA to initiate) and AA-HA essential information interchange (A), during which the AA exchanges information with all HAs providing information to effectively fulfil BS demand coverage: family power share, utility share per capita, family size, total demand, power surplus/deficiency, and power cost if applicable. (B) shows that only a subset of HAs is actively seeking power i.e. HA1-HA5 are active. In (C) HA1 is negotiating with all other HAs for an appropriate level of power to cover its BS demand; in this case HA9 has the appropriate power surplus (nearest available surplus power to cover the targeted power deficiency) and negotiations are initiated (D). (E) shows that a HA must scan all other agents before deciding from which it covers its deficiency. (F) shows that agent HA2 satisfies its power needs from HA7 only after scanning all other HAs. (G) shows that all HAs continually update the AA with the results of their power transactions. (H) shows a case when a HA (in this case HA4) is unable to identify the power suitable for its needs after scanning all other HAs, and hence does not initiate inter-agent negotiations with other HAs to borrow their surplus power. After completing a cycle, any remaining power can be deployed to cover the demand of HA4 (I).

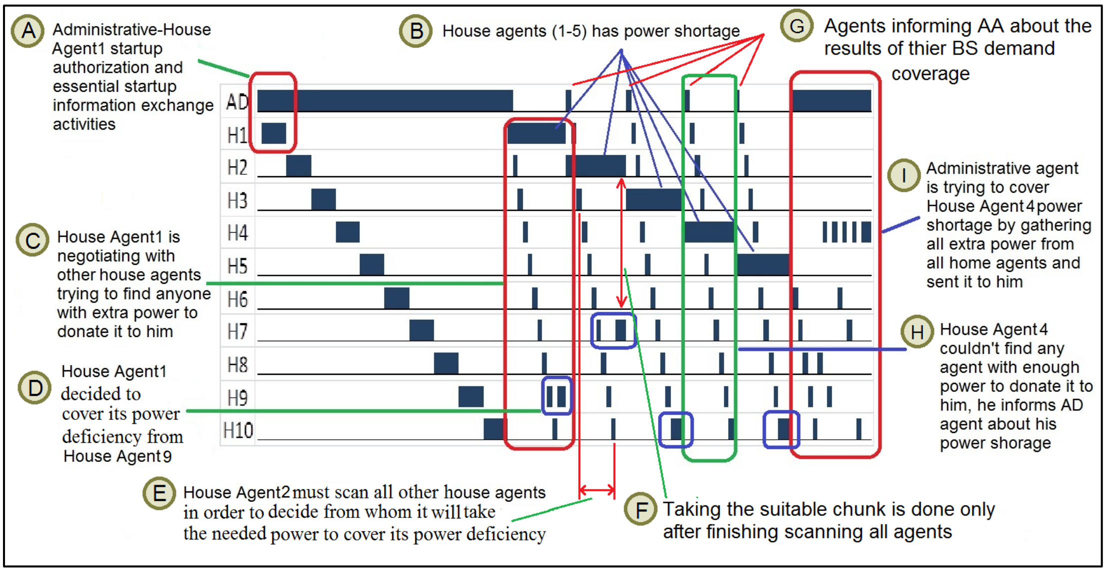
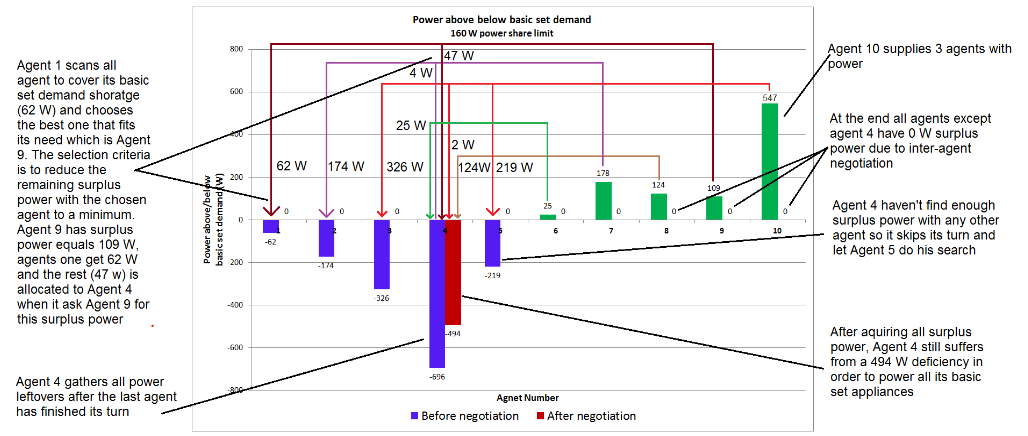


Figure 4.12: Inter-agent BS demand coverage negotiations.

To promote a more detailed understanding of the agent interactions, Figure 4.13 shows three different aspects of the process. Figure 4.13 (a) shows the available power for each HA before and after inter-agent negotiation. Here HA1 secures the needed power from the HA with the most suitable amount of surplus power, which is in this case HA9; the remainder follow the same principles i.e. HA2 (from HA7), HA3 (from HA10). It is evident that HA10 offers a significant level of surplus power, contributing to the covering demand of three HAs. This surplus power was insufficient to cover HA4, which, despite that, was allocated power aggregated from all other HA (HA6-HA10), reducing its power deficit from 696 W to 494 W. The result shows all HAs (HA1, HA2, HA3, and HA5) have met their demand and HA4 has reduced its total requirement; consequently HA4 trims its BS demand to fit the available power allocation. This demand coverage process continues to fulfil power allocation requests as long as it possesses a surplus. Figure 4.13 (b) shows the coverage staging of the BS demand shortage, which stood at 1477 W overall at the outset. In each step, one HA is allocated power from a HA thus covering part of the overall power shortage; only 494 W (HA4) remains unmet. Figure 4.13(c) shows the level of power for each HA. In the 3-bar graphs, the blue represents the power share allocated to it, the red represents the BS demand before negotiation; the difference represents the power surplus or deficiency for that HA. The green bar represents the BS power after negotiation. The majority of HAs have met their demand – manifest as levelled red and green bars - except as anticipated, in the case of HA4.

It is worth noting that the penalty on the system response time owing to inter-agent negotiations is expected to be tolerable due to several reasons; the size of the Kafaat residential quarter is a modest ~500 houses and the fact that inter-agent negotiation time delay is incurred only when the power share for a certain family is beyond its minimal requirements, a rare scenario under normal situations.



Agent 1 scans all agent to cover its basic set demand shoratge (62 W) and chooses the best one that fits its need which is Agent 9. The selection criteria is to reduce the remaining surplus power with the chosen agent to a minimum. Agent 9 has surplus power equals 109 W, agents one get 62 W and the rest (47 w) is allocated to Agent 4 when it ask Agent 9 for this surplus power

Agent 4 gathers all power leftovers after the last agent has finished its turn

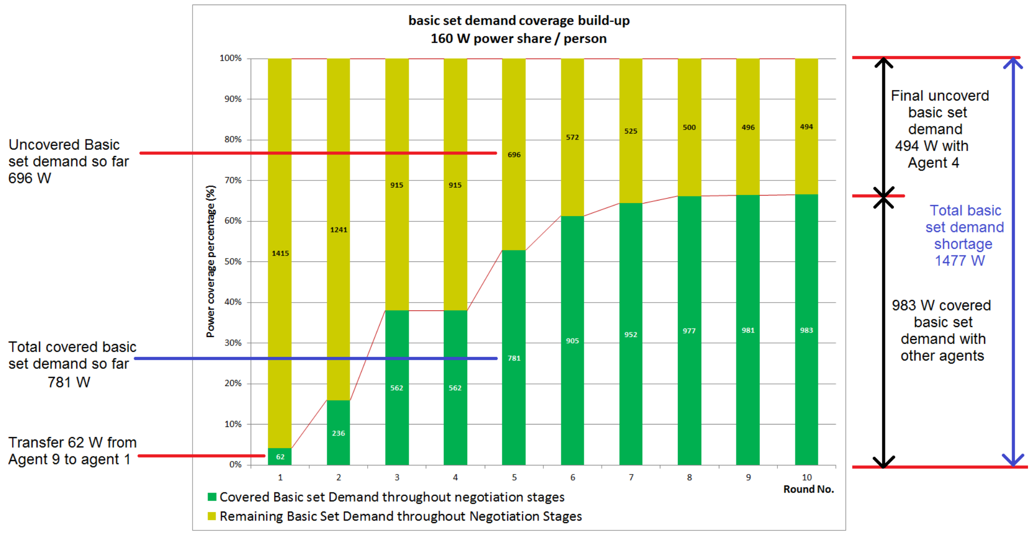
Agent 10 supplies 3 agents with power

At the end all agents except agent 4 have 0 W surplus power due to inter-agent negotiation

Agent 4 haven't find enough surplus power with any other agent so it skips its turn and let Agent 5 do his search

After aquiring all surplus power, Agent 4 still suffers from a 494 W deficiency in order to power all its basic set appliances

(a) power transfer among agents during inter-agent negotiations



Uncovered Basic set demand so far 696 W

Total covered basic set demand so far 781 W

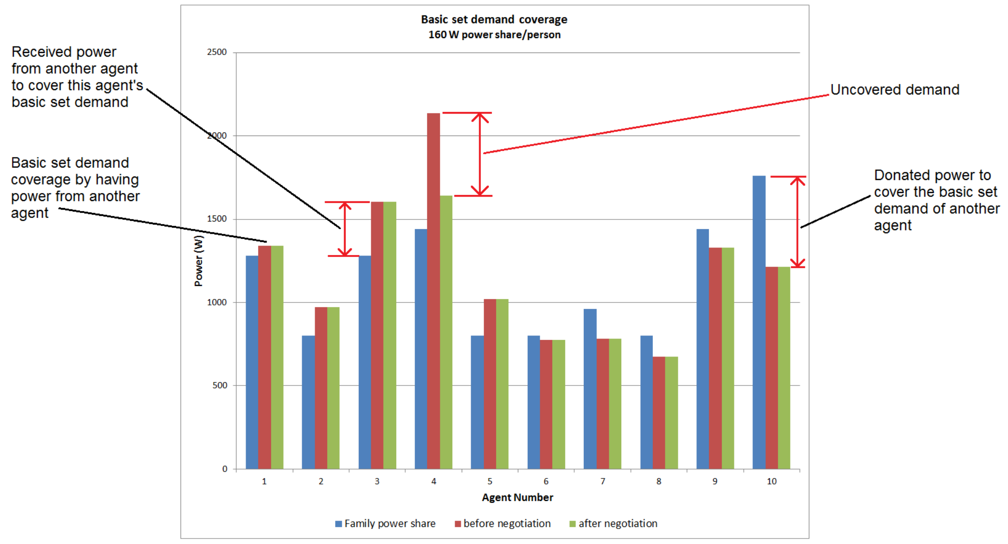
Transfer 62 W from Agent 9 to agent 1

Final uncovered basic set demand 494 W with Agent 4

Total basic set demand shortage 1477 W

983 W covered basic set demand with other agents

(b) demand coverage through different negotiation stages



Received power from another agent to cover this agent's basic set demand

Basic set demand coverage by having power from another agent

Uncovered demand

Donated power to cover the basic set demand of another agent

(c) power share and its power before and after negotiation

Figure 4.13: Inter-agent negotiation between 10 agents.

This inter-agent negotiation includes intensive start/request/reply operations characterised by a large number of command and data exchange operations (Figure 4.14). The 'red' plane shows the main commands that are exchanged, while the 'blue' shows the command descriptors exchanged during a negotiation session. The complexity of the negotiation depends mainly on the total number of agents and the number of those which have a power supply shortage.

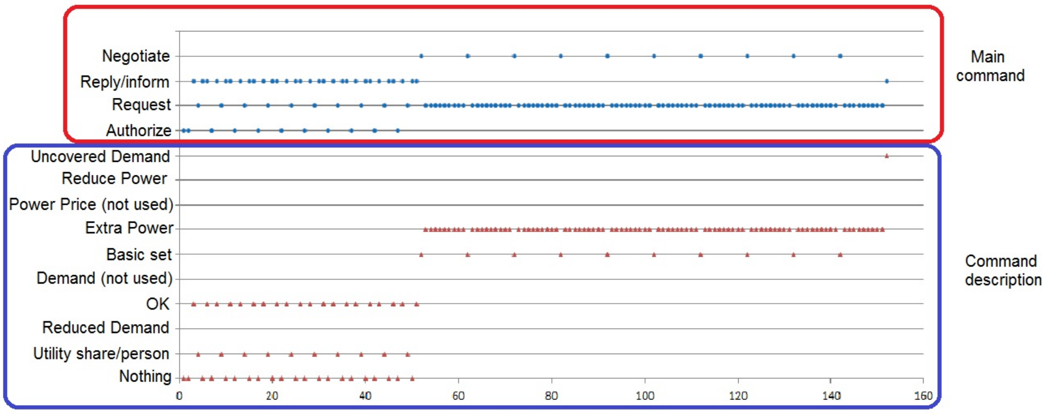


Figure 4.14: Agent response chart presenting authorise/request/reply operations between HAs during basic set coverage operations.

Stage 2 – Dynamic Adaptive HVAC Clustering (Phase 1 and Phase 2)

After BS demand is covered, the primary goal of the solution shifts to powering HVAC appliances on a one per house basis, using the power snooped from different GAs. The following phases relate to the summer[61] season, an important condition since this implies that the BS demand is covered from the aggregated surplus power and not from the utility. Figure 4.15 shows the operations executed in Phase I of this stage; at the outset the AA requests all HAs to send their AC, CO, and MF demand as well as the corresponding house temperature and humidity. The total number of participating HAs (N and later K) is thus known to the AA, as it can be set or requested from the system operator.

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[61] Relevant to some degree for winter, since the current strategy can also be applied on water and space heaters.

Upon the reception of the information, the AA construct four vectors for each quantity$\overrightarrow{P^{AC}}, \overrightarrow{P^{CO}}, \overrightarrow{P^{MF}}, and\ \vec{T}$, sorts all vectors in descending order, creates new vectors $\overrightarrow{Pt^{AC}}, \overrightarrow{Pt^{CO}}, \overrightarrow{Pt^{MF}}$twice the size of the originals, resets their entries, populating the new vectors in such a way that they contain in one half the original vector and the other half is zeros. It is essential for the AC vectors to have their zero cells positioned to the left while the remainder have their zero cells positioned to the right. The algorithm is then invoked to reach a decision whether it is possible to power all ACs in all houses on a one per houses basis or not. If it is possible, the task is complete and every dwelling is issued with the usage right to operate a single AC for the supply period.

Definition: *Usage rights:* are token-like authorisations for HAs to power their ACs ON for the stable supply period.

Definition: *Stable Supply Period:* is the period during which a certain level of surplus power is secured.

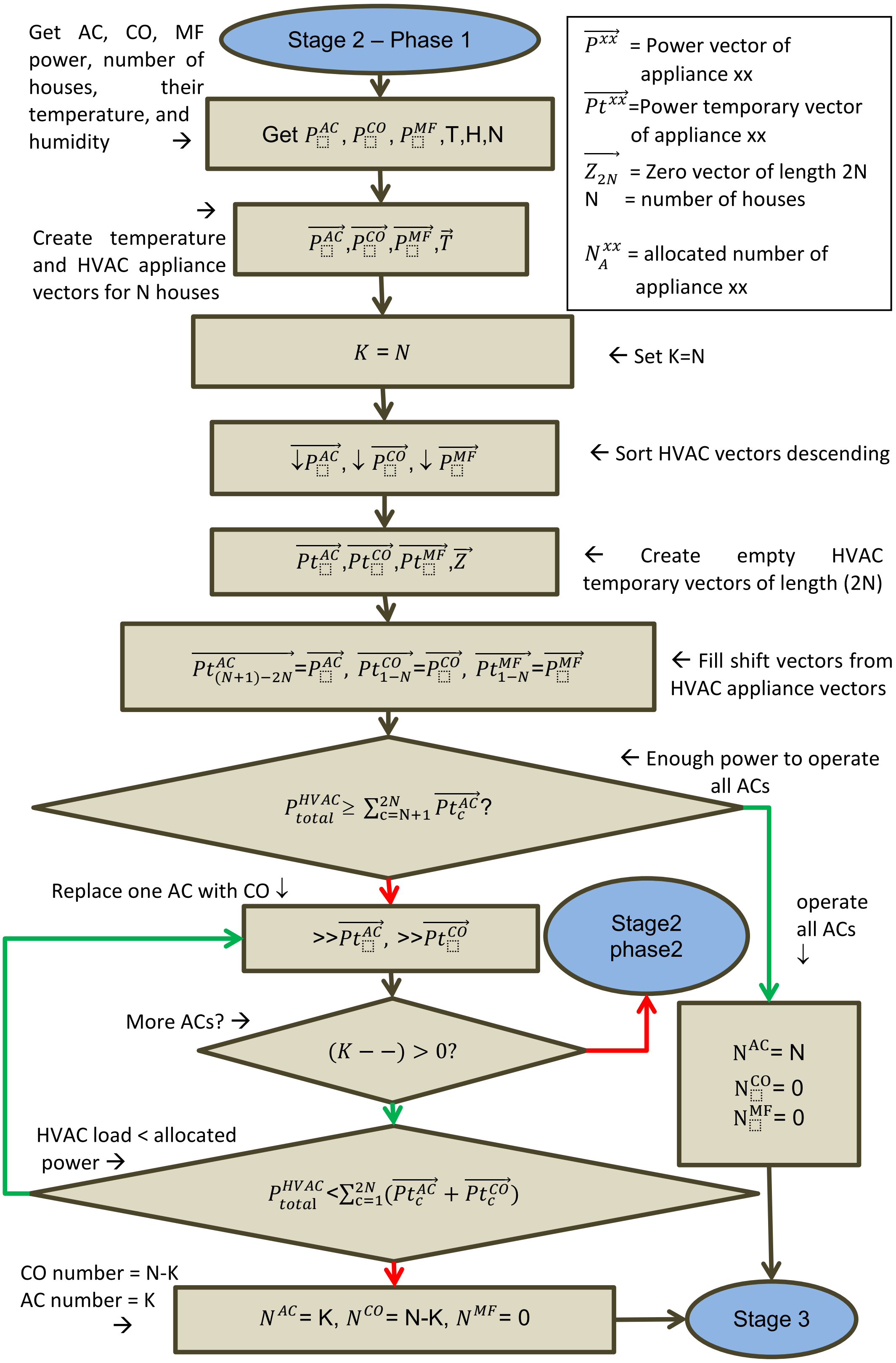


Figure 4.15: Stage 2 Phase 1 adaptive HVAC clustering.

If demand has not been met, then the vectors $\overrightarrow{P^{AC}}\ and\ \overrightarrow{P^{CO}}$ are shifted on place to the right, K is reduced by one, and both vectors are added. The purpose of the shift operation is to exclude the rightmost AC from the vector and at the same time insert one CO from the left, maintaining the total number of HVAC appliances equal to N.

$\overrightarrow{P^{AC}}\ and\ \overrightarrow{P^{CO}}$ are then added to determine the total demand to operate N-1 ACs and 1 CO. If this demand condition is satisfied, the strategy is moved to Stage 3; otherwise, the cycle is repeated. When the secured surplus power is relatively low, the cycle is repeated until all AC in the cluster are exhausted. Then the strategy reverts to Phase 2 of Stage 2 in which the cycle is repeated, but now with COs and MFs as alternatives HVACs. Their overall demand now becomes the cornerstone for all the decision-making processes. Figure 4.16 illustrates this stage. The number and mix of ACs, COs, and MFs used to form a cluster is determined by the available level of surplus power.

This mechanism is used to find the possible number of ACs, COs, and MFs that can be covered with the available surplus standby power and even though the same sequence of houses' HVAC are excluded every time, this has no net effect on the fair distribution of HVAC usage rights amongst houses.

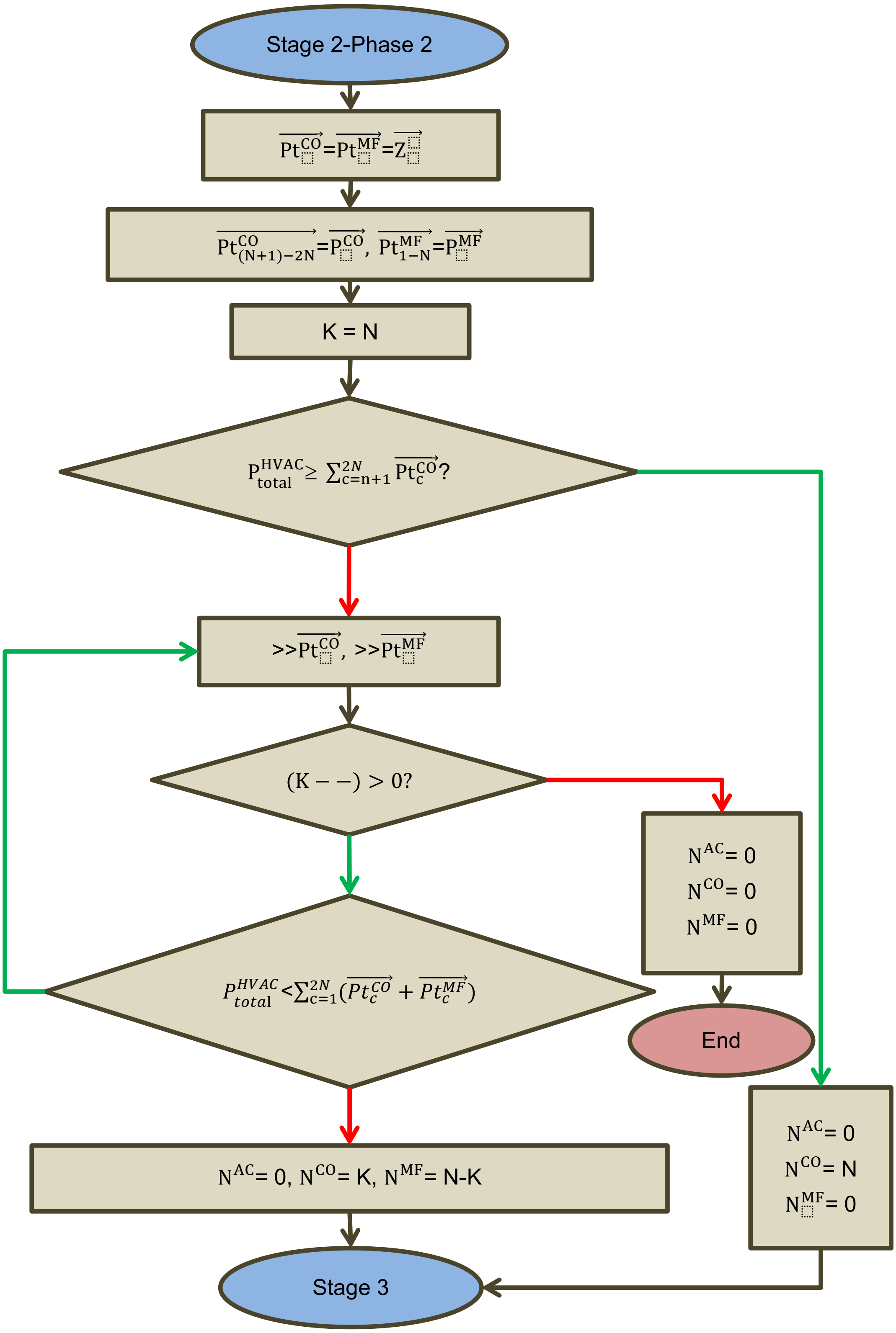


Figure 4.16: Stage 2, Phase 2adaptive HVAC clustering.

Stage 3 - HVAC Allocation Algorithm

In this single phase stage (Figure 4.17), the number of ACs, COs and MFs defined in the previous stage are allocated according to two types of protocols i.e. Fair Share (FS) and Temperature-Triggered (TT). The first allocates every HA the same usage time of each type of HVAC appliance and the second distributes according to the house temperature, where ‘hot’ environments are allocated ACs whilst ‘cooler’ ones have COs. The decision on which HVAC is to be powered is based upon the temperature of house; if this temperature exceeds a certain threshold, TT is triggered and otherwise FS is implemented.

The stage starts by determining whether the temperature threshold has been breached or not. On prohibitively hot days, the threshold is reached triggering the TT distribution, otherwise FS is utilized. If TT is selected, then the number of allocated ACs is checked; if any are available, then a number of ‘the hottest’ houses receive AC usage rights and the rest COs. If the number of allocated ACs is zero, then that proportion of ‘hot’ houses enjoy COs and the rest MFs as decided by the previous stage. Dwellings are powered according to their calculated power shares.

On the other hand, if the house temperature threshold is not exceeded, then the number of allocated ACs is checked and if it is more than zero then the number of allocated ACs and COs is checked to determine if they can be allocated in a fair manner. If the number of allocated ACs is zero, the same process is followed but with COs and MFs.

Definition: *Distributable HVAC Number* is the number of selected HVAC appliance pairs (AC and CO) or (CO and MF) that can be divided into an integer number of usage rights cycles e.g. for 20 houses if the number of ACs is 13 and the number of COs is 7, then it is not possible to distribute this number of HVACs fairly and an adjustment to the next distributable AC-CO number that can be powered by the available level of surplus power must be made i.e. 10 ACs and 10 Cos,2 groups each one with 10 houses meaning that the targeted time zone is divided into 2

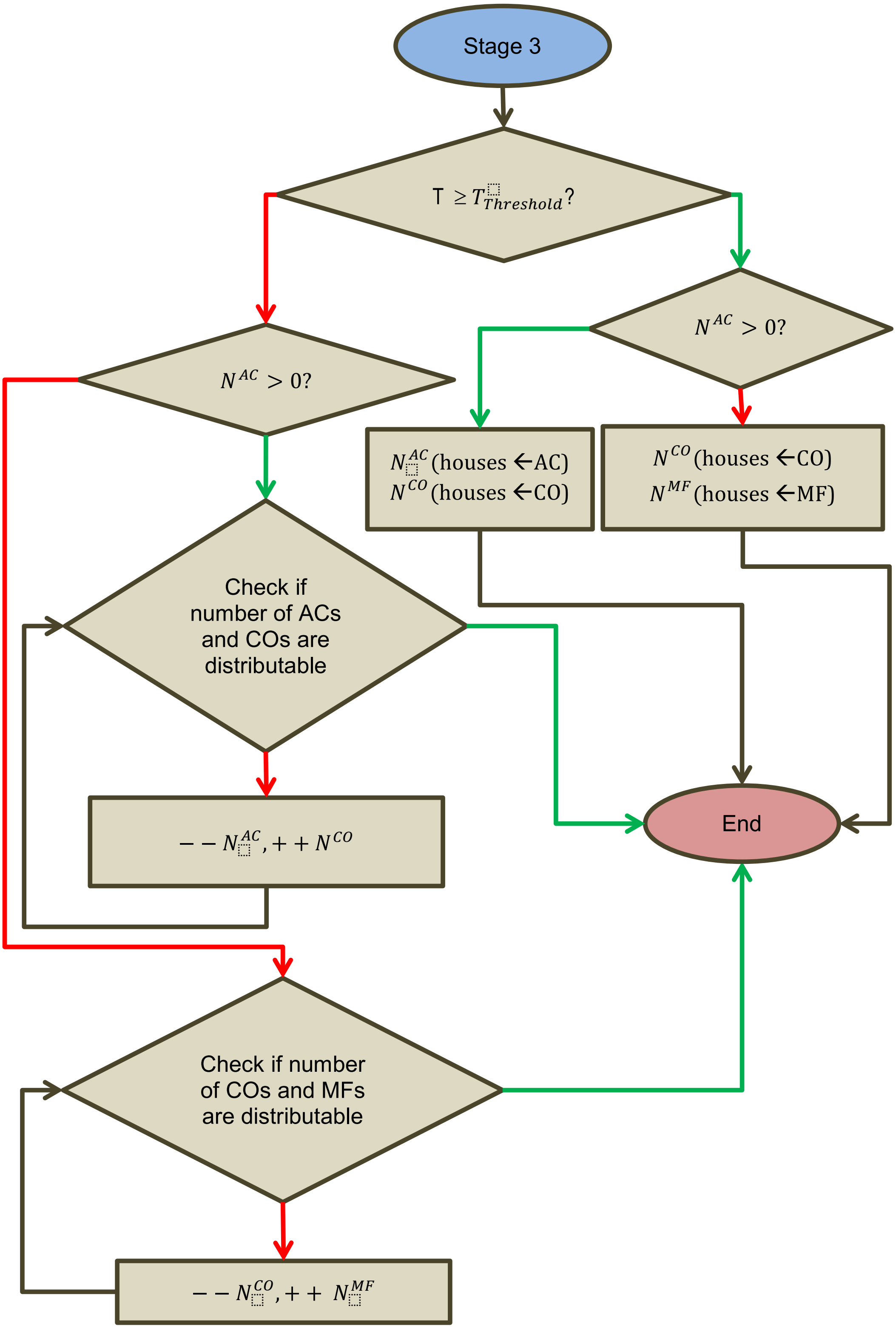
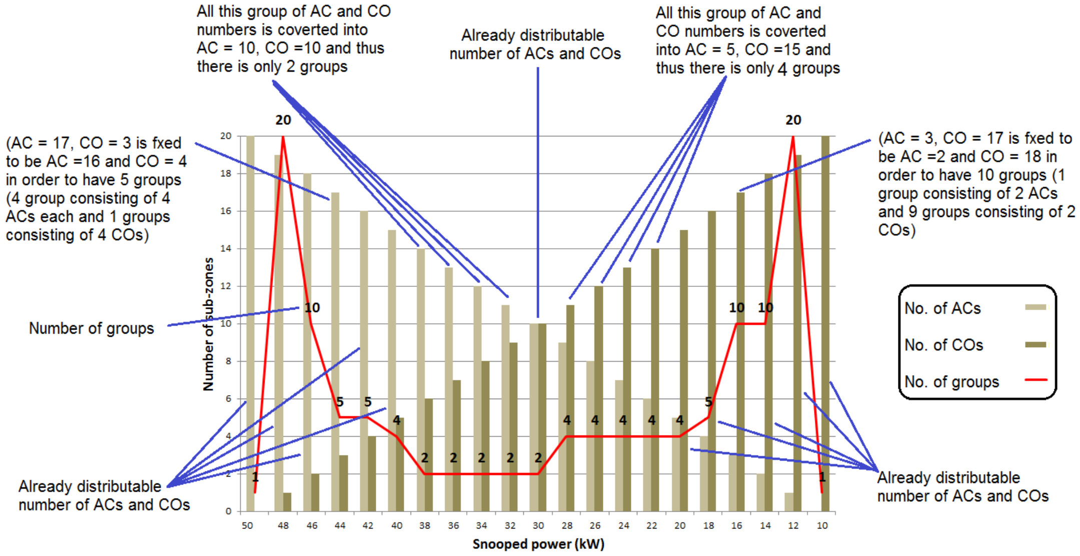


Figure 4.17: Stage 3 HVAC allocation.

sub-zones. During first sub-zone the first 10 houses are allocated ACs and the remaining COs; the situation changes during the next sub-zone.

The Distributable HVAC Number is best clarified by an example. If the HVAC clustering stage results in AC = 7, CO = 13, MF = 0 then this distribution is not compatible with FS principles. Then a nearest realisable cluster i.e. AC = 5, CO = 15, MF = 0 is established. Figure 4.18 shows this operation in more detail for 20 dwellings with a set of ACs (2500 W each) and COs (500 W each). For the purposes of the research, ACs and COs are set to similar ratings; although the principles are applicable to commercial HVAC appliances of differing ratings. This figure shows the number of ACs (light brown) and COs (brown) calculated from available power levels (10-50 kW) and the number of HVAC groups (red) possible from such an AC-CO combination. For example, when the available surplus power level is 46 kW it is possible to power 18 ACs and 2 COs, so in order to fairly distribute this HVAC usage rights among the 20 houses, time is divided into ((18+2)/2 = 10) divisions and during the first time division two households are allowed to operate their COs and the remaining 18 enjoy ACs; the next two households are forced to replace their 2 operational ACs with COs and so on in a sequential manner.



for: Air conditioner = 2500 W, Air cooler = 500 W

Figure 4.18: HVAC distribution and grouping.

Certain combinations of ACs and COs are compatible with the approach whilst others are not. The resulting number of groups depends on the fixed numbers of ACs and COs.

Figure 4.19 shows HA grouping and the exchange of usage rights amongst different groups for 30 dwellings (a strong function of the total number of HVACs).

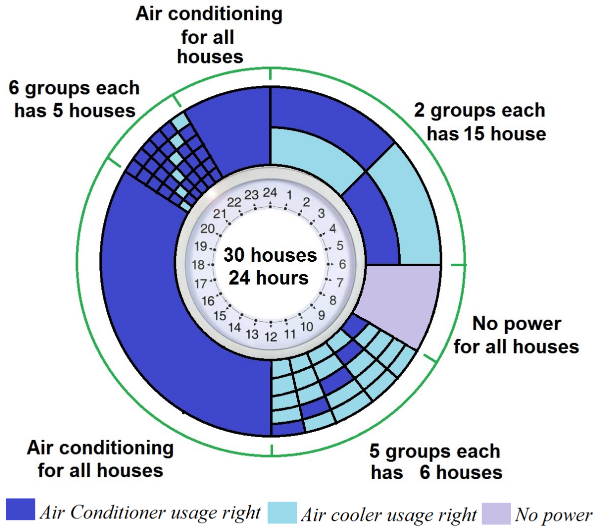


Figure 4.19: HVAC usage rights distribution under a fair share distribution scheme.

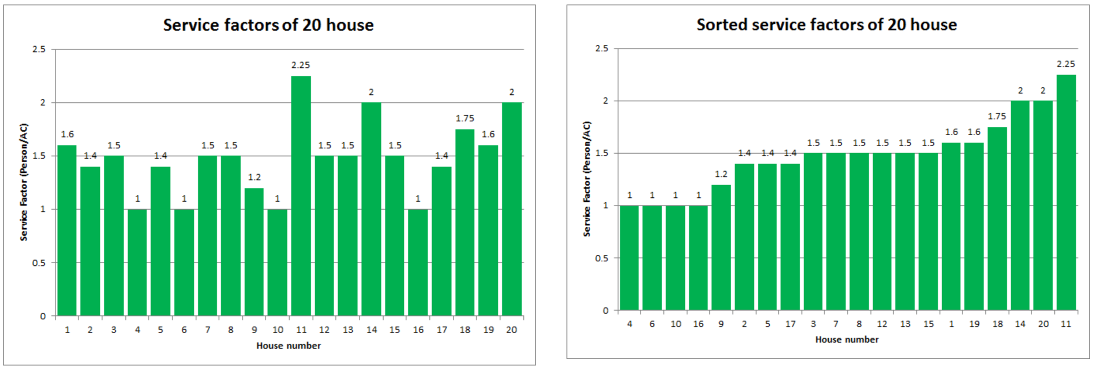
4.8 Cyclic Blackout Prevention

The strategy has been developed not only to mitigate cyclic blackouts but can be extended to a prevention mode. The main principle underpinning prevention is that when the demand supersedes available supply, the system starts to interlock ACs with COs in individual dwellings. It is assumed – validated by an extensive field survey - that each dwelling has multiple ACs and one CO.

In managing a demand coverage deficiency mode, ACs in client homes are turned OFF sequentially, starting with the living room AC, followed by the bedrooms, to avoid shedding more than the exact number at that instant. The shedding of ACs in this manner is an attempt to maintain a habitable environment but nevertheless continues until the demand coverage is balanced. The assumption is that the living room is equipped with multiple HVAC appliances (AC and CO) and thus the powered down AC is replaced with a CO. This is only the case for the main living room area; all other rooms equipped with ACs do not have a replacement option.

The allocation is based on two main principles; HVAC Total Usage Period (HTUP) and HVAC Service Factor (HSF). The former represents the total amount of time (in minutes) that the AC is powered throughout the day, while the latter is the number of people in a certain family serviced (cooled) by a certain AC calculated by dividing the number of people over the number of operational ACs in their home e.g. a large HSF means that a single AC serves a lot of people and vice versa. These two factors provide a logical basis for fair decision making.

If the initial switch out of the living room AC is insufficient to match the limited utility, then in turn, the bedrooms ACs are turned OFF sequentially, classical shedding of demand since there are no HVAC alternatives in the bedrooms to interlock. Figure 4.20 shows the calculated service factor for 20 dwellings (Figure 4.20 (a)) and the same HSF after sorting (Figure 4.20 (b)). The latter is also an indirect indication of the wealth of the neighbourhood, since smaller HSFs represent more ACs deployed in a single dwelling.



(a) (b)

Figure 4.20: HSF for 20 houses (a) not sorted (b) sorted

Figure 4.21 depicts the principles of the cyclic blackout prevention strategy. At the outset, the amount of available utility power is recorded and the deficiency in demand estimated. Then the two HVAC load interlocking and shedding principles HTUP and HSF are invoked. If the former is adopted, the HTUP is calculated for every AC in all houses and are sorted accordingly; if the latter is adopted, then the HSF for each family is calculated and houses are sorted accordingly. The prevention cycle is initiated starting in the living area by checking the status of its AC; if it is turned OFF, the system moves to the second house to carry out the same task.

Conversely, if the AC of the living room is operational, the system checks if the CO is also operational. Then, only the AC is turned OFF; otherwise if the CO is inactive, the AC is turned OFF and the CO is turned ON. The system repeats the cycle until the demand is covered. The spine of the cycle is migration from house to house, with a view to shedding the demand of all living rooms ACs, followed by powering down of the next ACs in the hierarchy.

4.9 The Rationing Smart Meter

An important element of any cyclic blackout mitigation and prevention solution is an effective power monitoring and supply control infrastructure. In this solution, a monitoring and intervention approach is implemented in the form of a modified version of the current smart meter tasked with the monitoring and control of the amount of power consumed by customers. The RSM provides the ability to ration power supplied to individual customers according to the criteria defined and implemented in the approach. Figure 4.22 shows the block diagram of a RSM founded on a microcontroller responsible for managing and executing key tasks and controlling several modules; firstly, an energy/power measurement unit, responsible for recording the customer’s power consumption. Secondly, interface enabling the RSM to communicate with the utility. Various types of communication links can be envisioned and their selection is implementation-specific. Thirdly, another interface unit that connects the RSM to any power management or monitoring modules, such as the local (house) controller; nothing prevents this module from having its own communication capabilities, which gives the RSM an increased robustness in terms of data exchange. Fourthly, a mini keyboard and a suitable screen, enabling users to input basic commands to the RSM e.g. restart power after cut-off, test the RSM, display consumption statistics, display current

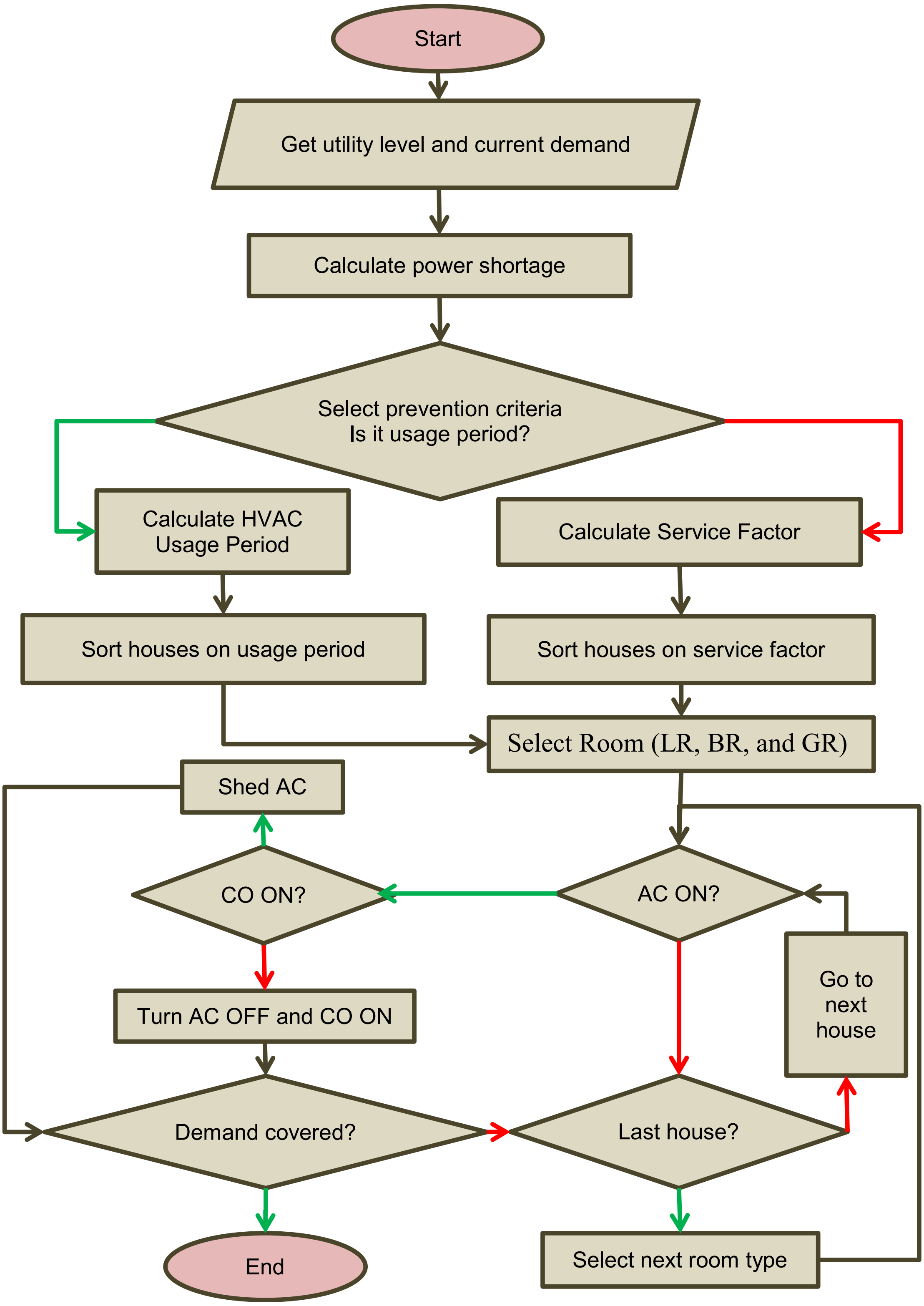


Figure 4.21: Cyclic blackout prevention.

power share. Finally, a power distribution control module consisting of a group of relays used to connect/disconnect each dwelling from the LV distribution network whenever necessary.

This module offers two monitored and controlled lines connecting appliances to the RSM; the first is a continuous power supply line for basic set appliances (lights, fans, TV, refrigerator.), while the second is the HVAC power supply line. Both lines are set supply limits by the main controller, if the limits are breached, the RSM cuts the power off e.g. when customers connect more load than the rating of the supply lines.

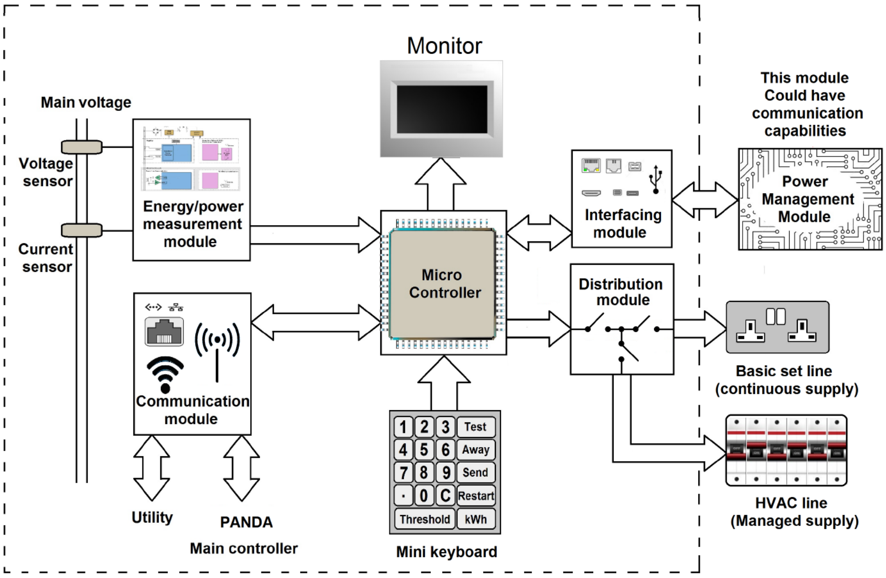


Figure 4.22: The Rationing Smart Meter.

In general, a RSM comprises the main parts of a normal smart meter but extended with additional multi-path power supply monitored and controlled lines, mini keyboard and a small display. The additional communication capabilities between the RSM and the main controller can be realized not only through the communication module but also through any module that has such capabilities connected through the interfacing module such as the Embedded Control Unit [11].

Figure 4.23 shows the RSM monitoring and control functions. The RSM receives the power share allocation from the main controller, connects power to the dwelling

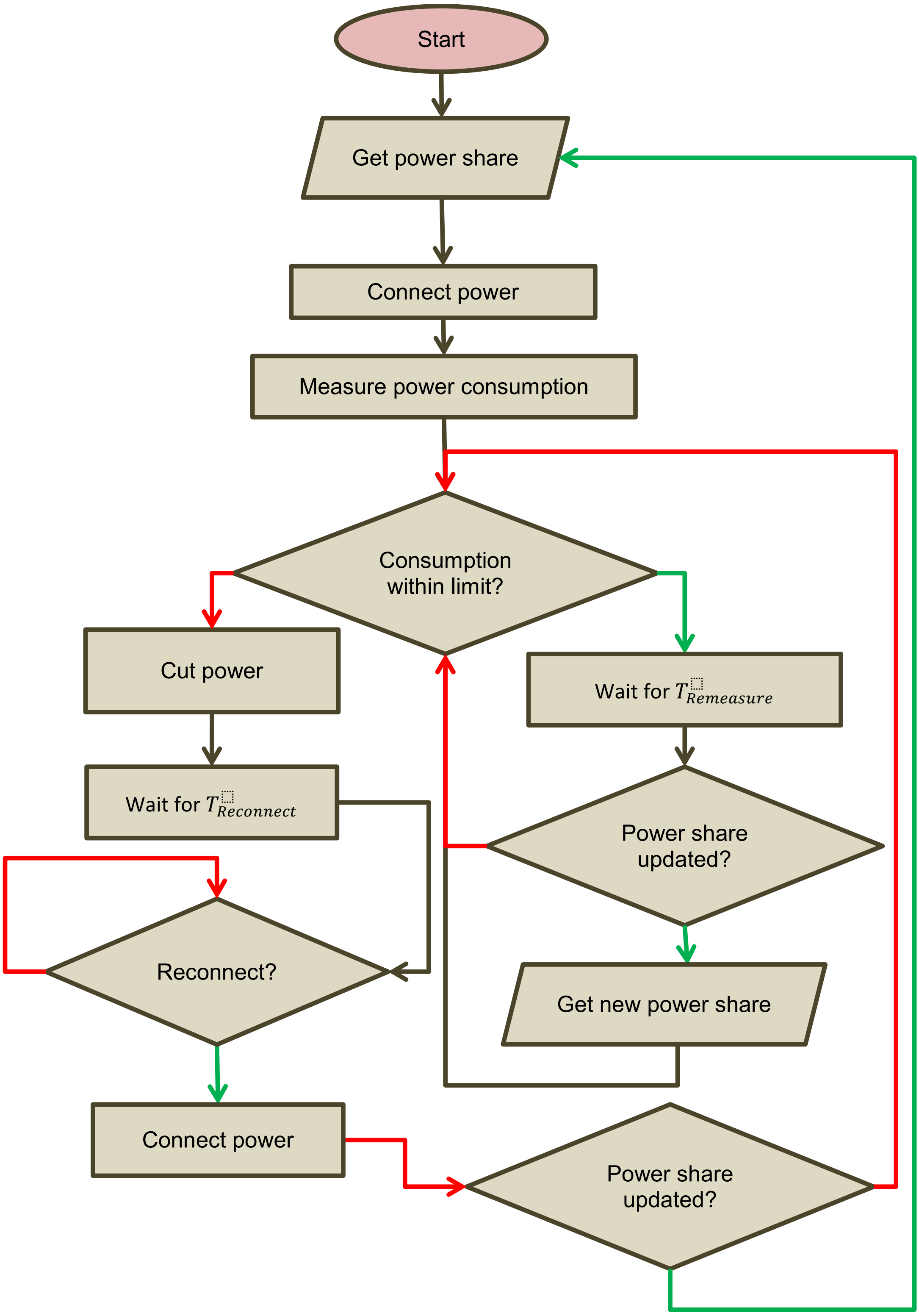


Figure 4.23: RSM power share monitoring and control operations

(Other typical smart metering operations are not included for clarity) and monitors the amount of power consumed. If outside the permissible limit, the power is cut; otherwise, a waiting of $T_{Reconnect}$ is invoked, checks if the reset button is activated by the customer, interrogates for a power share update and if so, it updates the power share allocation and re-connects power to the house. If the consumed power is within the permissible limits, then the RSM waits for $T_{Remeasure}$ and checks for a share update, if so the power share allocation is updated.

4.10 Summary

A cyclic blackout mitigation and prevention strategy referred to as PANDA has been developed to address chronic and peak time power shortages all year around. Operation in its cyclic blackout mitigation mode is by harvesting all surplus power within the vicinity of the residential area from all standby generation facilities willing to cooperate. The approach aggregates all surplus power into a unified daily schedule, to be used to provision power to that residential community.

The strategy uses this surplus power to operate a basic set of appliances in each house plus one HVAC appliance. The basic set excludes power-hungry appliances such as hair dryers. The type of the single HVAC appliance powered in each house is a strong function of the amount of available surplus power; ACs, COs, MFs or a combination of any two can be powered except ACs and MFs which is excluded from the current strategy but can be considered in future versions.

The usage rights of this combination of HVACs are distributed either as equal shares of each type or based on the temperature inside the houses where hot houses are allocated ACs while the remainder are serviced through COs. Robust evidence proving that interlocking ACs and COs is an effective approach has been provided [132] especially in hybrid mode applied to large commercial buildings and complexes. The ultimate goal of the proposed solution is to provide a sound Quality of Experience[62] (QoE) level to all customers, with a good level of comfort during power OFF periods.

The strategy in its cyclic blackout prevention mode follows similar principles as in mitigation mode, but is based on turning OFF ACs and/or replacement of ACs with other less power hungry HVACs such as COs following a structured protocol with the added benefit of managing demand profiles especially in prohibitively hot environments. Blanket AC load shedding is not executed, but on a single AC per dwelling basis through informed powering down of AC from each house. A hierarchical powering down cycle protocol is followed until a power balance is achieved. The basic evaluation of the application of the approach in its two modes has shown that the system functions as expected and achieves the stated goals.

Due to the limited power supply, ensuring that customers consume the rightful share of power is an important factor that governs the success of the proposed strategy. RSM, an enhanced variant of typical smart meters, is introduced and used as an integral part of the proposed approach. The main role of the RSM is to receive from the main (central) controller a power share (ration) for each family, monitor their power consumption, provide alerts if their demand is about to exceed their power share, cut the power if not responsive to alerts, and provide the ability to restore the power locally.

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[62] Quality of experience (QoE or QX) is a fast emerging multidisciplinary field based on social psychology, cognitive science, economics, and engineering science, focused on understanding overall human quality requirements [258]. It is the difference between the customer's expectations and perceptions for a certain service. The difference between it and Quality of Service (QoS) that the former measures the difference between what a customer expected, and what they actually received while the latter refers to the technical operational aspects of a service, e.g. time to answer support calls, capacity, and transport. QoS can be considered as measuring service quality "from the inside out" while QoE as measuring quality "from the outside in." [253]

Chapter Five
The Field Study

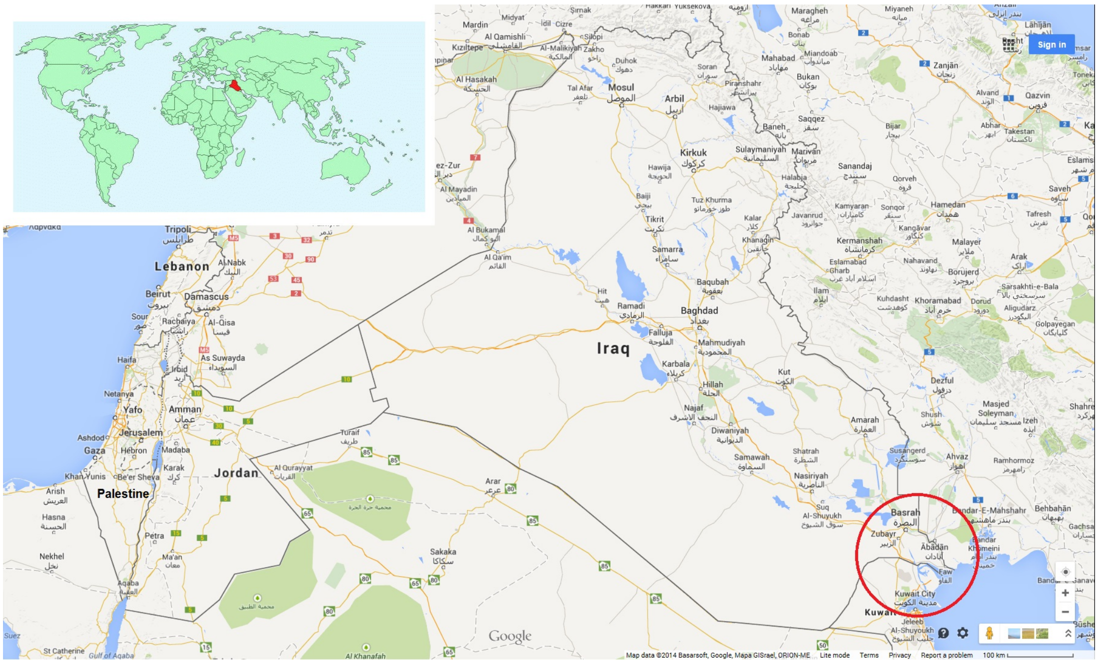
5.1 Preface

This chapter describes a representative residential area in Basra, Iraq the focus for the case study. The detail of a field study aimed at mapping resources, data about the area, its inhabitants and their energy consumption patterns is presented, developing a clear statement of the power shortage problem and the available resources. The results provide a deeper insight of the targeted population and their appliances contributing to the total demand in the residential area.

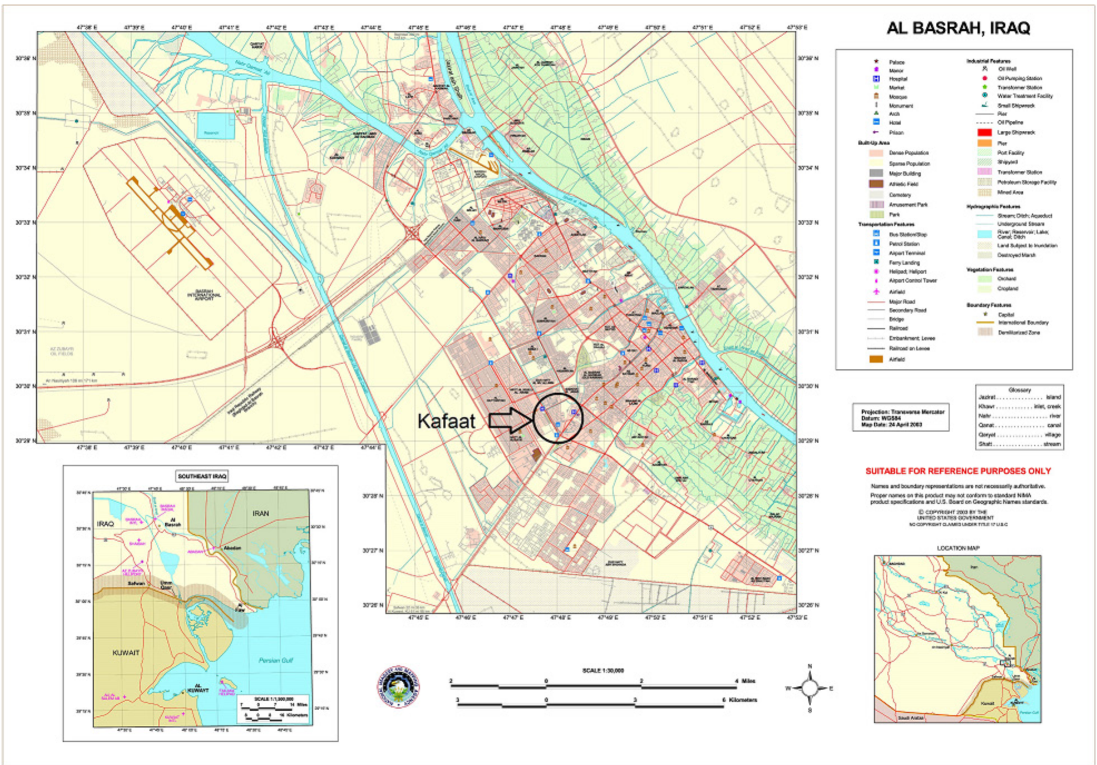
5.2 Why Iraq?

Iraq (Figure 5.1) is struggling to recover under severe power shortages as a consequence of a combination of the destruction of its power system during the war, the subsequent sanctions periods followed by a rocketing increase in demand owing to an extensive refurbishment campaign. The severe challenge is further exacerbated by the extremely hot weather during summer when the air temperature reaches 56 °C in cities like Basra.

These factors have resulted in damaging cyclic blackouts that have hindered Iraq's recovery for the past 18 years [35]. Several serious attempts have been initiated to solve the power shortages, such as building new power stations, connecting Iraq with the Iranian grid, adding mobile generators to the grid and renting several power ships (Figure 5.2) [23]. However all interventions have been overtaken by the ever-escalating demand, especially during summer when peak demand reaches double that of the available supply.



(a) Iraq with Basra city marked [222]



(b) Basra city with Kafaat residential quarter position [223]

Figure 5.1: Map of Iraq showing the location of Basra.

Figure 5.2: Turkish power ship (barge) in Basra [224].

Figure 5.3 shows the projected Iraqi peak electricity demand 2012-2017.

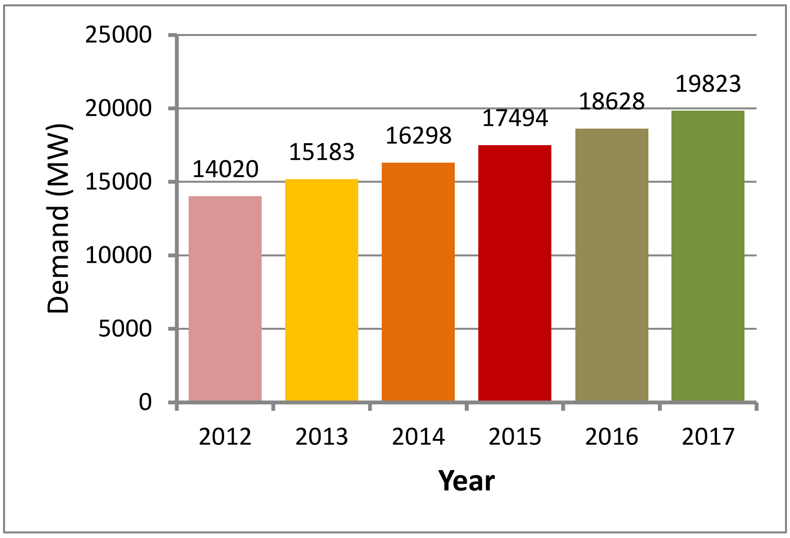


Figure 5.3: The projected Iraqi electricity peak demand 2012-2017 [225].

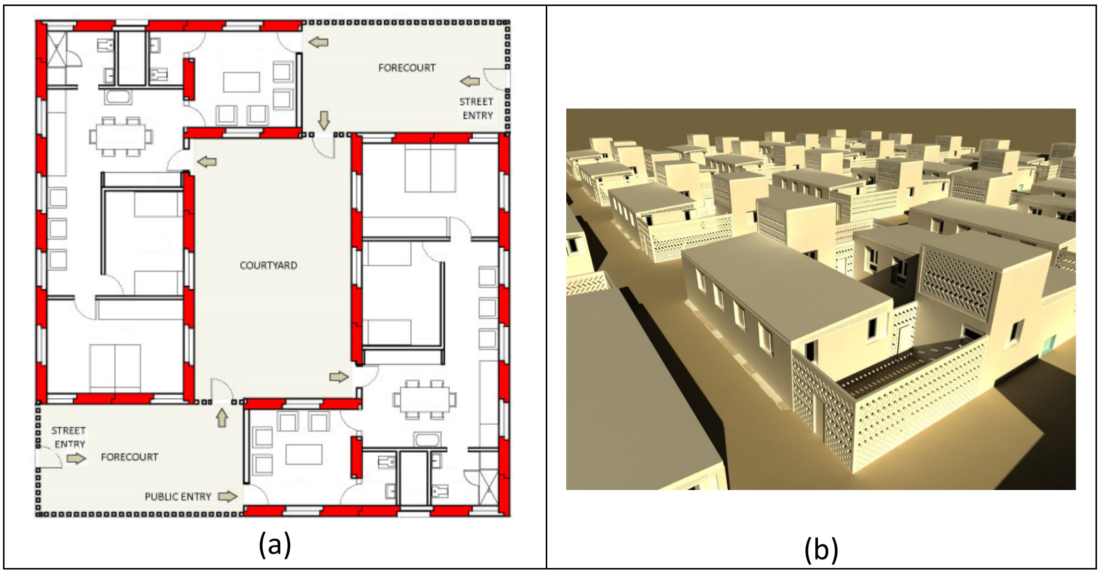
Other factors hinder the provision of an appropriately dimensioned power system such as the absence of detailed energy consumption data; the absence of data monitoring and logging in newly refurbished substations; the destruction of SCADA systems; and absence of co-operation and co-ordination between power authorities and consumers. The combination of these factors has driven the Iraqi power shortage into a chronic mode. Iraq is however a relatively wealthy country with ambitious, open-minded, and hard-working people amenable to adopting and implementing any reasonable solution to cure major challenges.

Basra, the southern oil producing governorate, is selected as the used case since it is the location of many wealthy industrial companies such as oil-producers, petrochemicals, and steel. Basra has secured a levy of $0.5/barrel of the exported oil selling price to be deployed in developing its infrastructure, which in turn makes its administration receptive to any promising solutions to the region's major challenges.

Basra is also in one of the hottest regions in Iraq and the only major city with a coastal line creating intermittent periods of high humidity each year.

5.3 House Architectures

Relatively old builds follow traditional Arabic houses based on eco-friendly designs and naturally insulating building materials such as brick, wood, and soil. Rooms are built around a central uncovered courtyard and one or more uncovered forecourts (Figure 5.4).



(a) (b)

Figure 5.4: (a) A typical Arabic house design and its [226] (b) 3D prospective within a complete neighbourhood [227]). Notice the open courtyard in the middle).

The outside and inside supports are two parallel walls made from bricks with the gap between filled with soil. The ceilings are usually made from four layers (bricks on the outer part of the ceiling, soil, supporting wooden bars, and finally a decorated wooden layer that represents the inner part of the ceiling) as depicted in Figure 5.5. Inside temperature is controlled through properly-placed openings in the ceiling and the doors which creates natural air cycles and routes throughout the house.

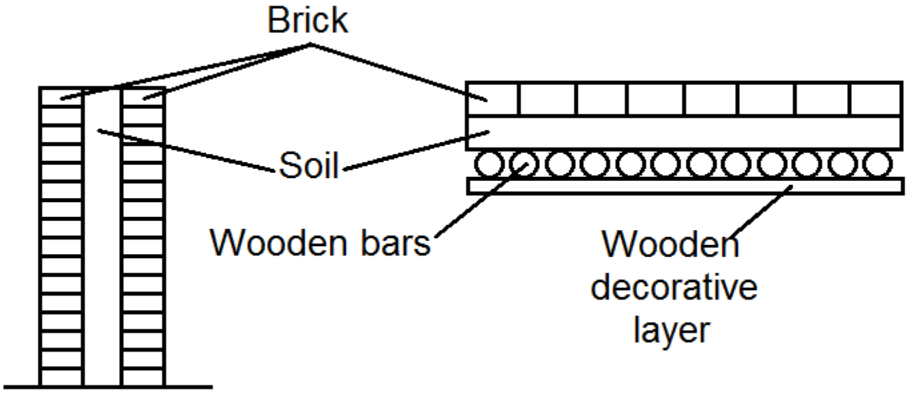


Figure 5.5: Old Iraqi dwelling wall (left) and ceiling (right) intersections show the use of multi-layer naturally insulating materials.

Contemporary Iraqi residential builds however rely on concrete and steel, motived by the desire to provide maximum protection during war periods. Figure 5.6 shows a modern Iraqi dwelling; notice the unpainted wall on the right side of the house revealing the cement-based nature of the building.

Figure 5.6: A modern Iraqi house [228].

Unfortunately, such concrete units have no insulation of any kind and rely mainly on continuous air conditioning to provide cooling, stimulated by cheap electricity prices in Iraq which are nearly eight times lower than the average residential electricity price as estimated by the Organization for Economic Co-operation and Development (OECD) in 2010 [3]. This coupled with other factors, has created a fast growing power demand continually outstripping available supply, despite of all intervention measures.

5.4 Kafaat Residential Quarter

The residential Quarter "Kafaat" (Figure 5.7) was selected as the focus of the use case and a field trip at the outset of the research mapped the residential area, its inhabitants, the nature of the demand, and generation portfolio.

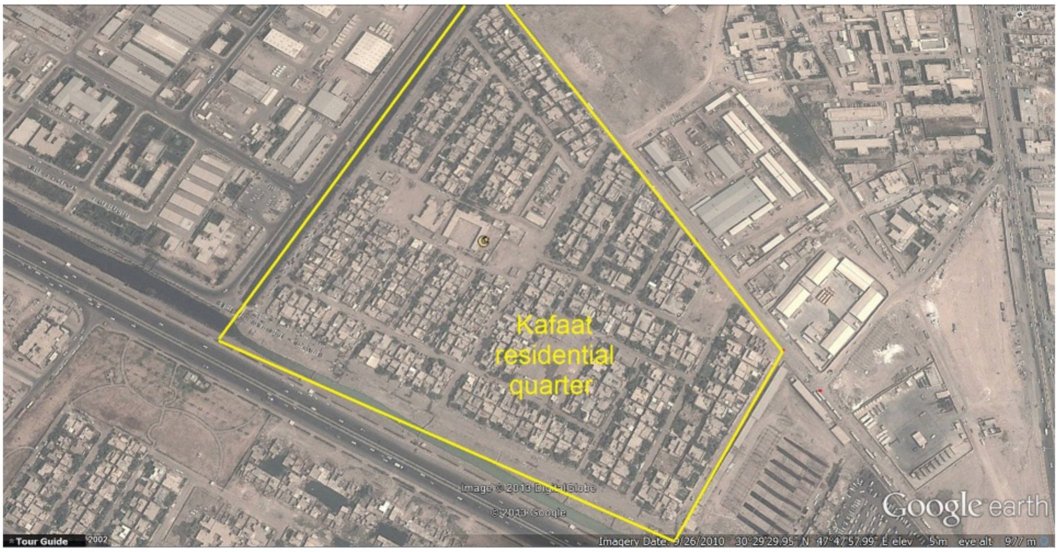


Figure 5.7: Kafaat residential quarter.

The mapping also included consultations with the local power administration to gather more extensive information on the Low Voltage Distribution Network (LVDN) structure; power generation, delivery and distribution; cyclic blackout periods, and causes; seasonal variations; staff; equipment; degree of cooperation and collaboration, and data logging procedures. The field study also included visits to Basra City Council, South Oil Company (SOC), hospitals, medical centres, and community generation facilities to record their round-the-year loads, the level of surplus of power, location, availability, operational time tables, seasonal fluctuations, energy cost/kW, and the terms of cooperation set by the generation facilities within and around Kafaat.

The selected Kafaat residential quarter is shown in Figure 5.8 with neighbouring major complexes; to the north is the SOC complex, to its east the medical complex containing a public hospital, college of medicine, and the medical training complex and the Basra City Council service centre, while to its west is a private hospital and finally to its south is the main bus station.

Figure 5.8: The major complexes surrounding Kafaat residential quarter (red lines).

Figure 5.9 shows the Kafaat residential quarter (red Quadrilateral shape) and its LV distribution network (yellow lines) branching from the local substation at its centre (blue square); the green circles are the distribution transformers and some distribution lines are routed to neighbouring areas.

Figure 5.9: Kafaat Substation and accompanying LVDN.

Kafaat boasts a plethora of community (commercial) and standby generation facilities; Figure 5.10 shows the position of these generators ranging from 250 kW to 10 MW.

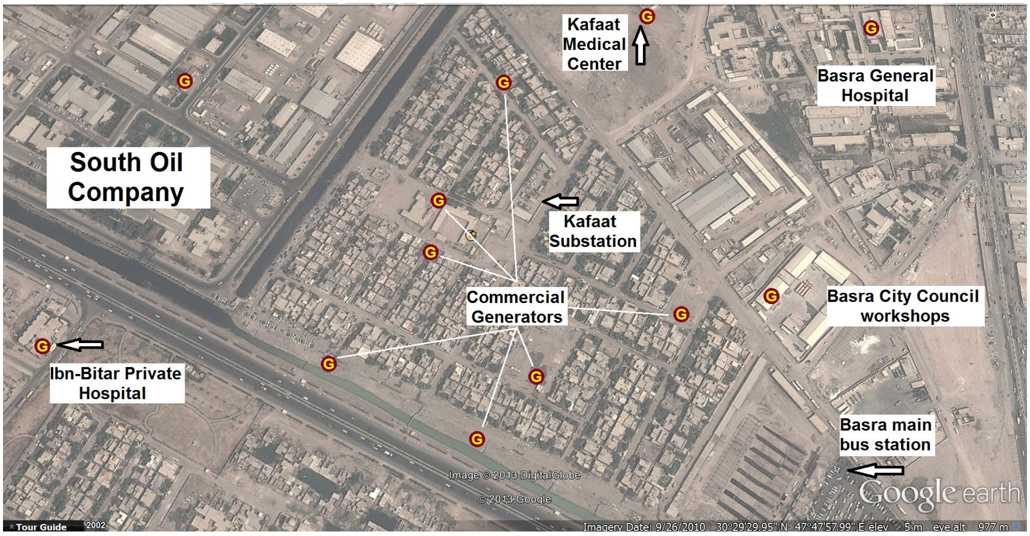


Figure 5.10: Kafaat generation facilities.

5.5 Standby Generation

One of the options in managing chronic power shortages is to harness the available standby generation resources in nearby establishments (Figure 5.10). A mapping of appropriate facilities around Kafaat area highlighted a mix of standby generation (Table 5.1):

1. **Southern Oil Company Administration and Central Workshops,** a 10 MVA standby generation facility. This big complex has a special tri-period power usage pattern that switches modes during the day and during different seasons. SOC depends on its standby generation only during parts of the day and not on the intermittent utility. The tri-mode demand is shown in Table 5.2.
2. **Basra City Council Workshops** following a normal work timetable (6 hours, 8 am – 2 pm).
3. **Hospital Generation Facilities,** two hospitals and one medical centre:
    a. Basra General Hospital
    b. Ibn Bitar private hospital
    c. Medical training complex

Although all hospitals are connected to what is known as the Critical Utility Line - a 24 hour continuous supply not included in any daily cyclic blackout routine - they still own standby generation for general utility failure cases. The standby generation usage is completely unpredictable, since it is strongly tied to the total utility power loss. Figure 5.11 shows some of the operational standby generation facilities (Figure 5.11(a)) and three unused standby generators (Figure 5.11(b)). This amount of underutilized standby generation, if properly deployed and coordinated, is sufficient to provide a means to mitigate severe power shortages.

Table 5.1: Summary of generation mix within and around Kafaat area.

	Ownership	Rating	Backup	Summer Load		Winter load		Type	From	To
Public										
1	SOC	10 MVA	unknown	8 am - 2 pm → 5 MVA 2 pm - 8 pm → 1 MVA 8 pm - 8 am → 2 MVA		8am - 2pm → 2.5 MVA 2pm - 8pm → 0.75 MVA 8pm - 8am → 1.5 MVA		Public	8am - 2pm 2pm - 8pm 8pm - 8am	
2	Basra Public Hospital	2×1000 kVA 1×400 kVA 2×250 kVA 1×360 kVA	X 2 of all types	2 MW	77 %	1 MW	38 %	Public	Standby	
3	Health centre	175 kVA	None	80 kW	57 %	60 kW	43 %	Public	Standby	
4	Ibn-bitar private hospital	3×375 kVA	375 kVA	253 kW	22 %	200 kW	18 %	private	Standby	
Basra City Council Generator										
5	Basra city Council workshop	750 kVA	None	540 kW 0 kW	90% 0%	220 kW 0 kW	37% 0%	Public	8 am 2 pm	2 pm 8 am
Community Generators										
6	Community 1	500 kVA	236 KVA	168 kW	42 %	62 kW	16 %	Community	12 pm	6 am
7	Community 2	400 kVA	None	106 kW	33 %	44 kW	14 %	Community	12 pm	6 am
8	Community 3	350 kVA	None	124 kW	44 %	45 kW	16 %	Community	continuous	
9	Community 4	350 kVA	250 KVA	106 kW	38 %	45 kW	16 %	Community	continuous	
10	Community 5	250 kVA	None	93 kW	47 %	40 kW	20 %	Community	12 pm	6 am
11	Community 6	250 kVA	None	53 kW	27 %	36 kW	18 %	Community	12 pm	24
12	Community 7	200 kVA	None	106 kW	66 %	45 kW	28 %	Community	12 pm	12 am

- All figures were taken during the field trip to these generation facilities
- Used Power Factor is (0.8)

Table 5.2: SOC annual demand.

Season	Hour during the day		
	8-14	**15-20**	**21-8**
Summer	5 MVA	1 MVA	2 MVA
Winter	2.5 MVA	0.75 MVA	1.5 MVA
Spring & autumn	1.5 MVA	0.75 MVA	1.25 MVA


(a) (b)

Figure 5.11: Standby generation facilities in (a) Basra General Hospital (within the fence) and (b) three unused units.

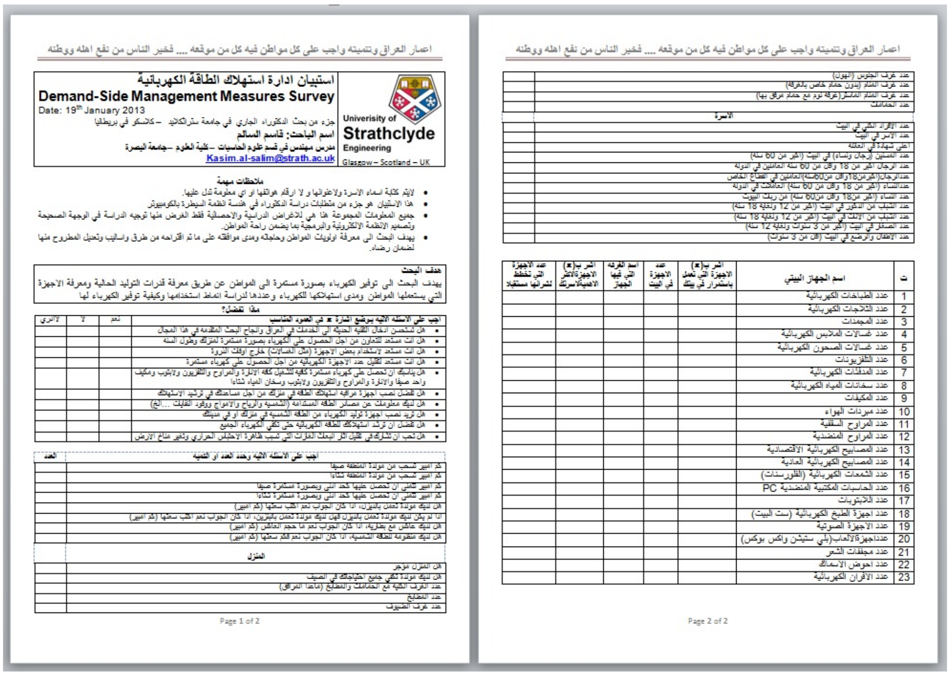
4. **Community Generation Facilities,** privately-owned commercial projects that sell power on a 'per ampere' basis. Within Kafaat, there are seven community generation facilities (Table 5.1) with different capacities, following different time tables and tariffs (dependent on their operating hours). Compared to people's income, community generation power prices are expensive (~150 US$/kW/month for a 24 hour standby service). The local government, in its attempt to mitigate power shortage offered to supply these generation facilities with fuel at reduced prices and pay half their operational expenses during summer months (June to August). This initiative provided sufficient motivation for consumers to engage, which created an overwhelming demand that resulted in the majority of consumers being unserved, owing to the limit in available generation and the uncontrolled and unrestricted reservation of such power, based on a first-come-first-served basis.

5.6 Demand Profiling

In order to secure a detailed mapping of customers and their demand, a survey (shown in Figure 5.12 - written in Arabic) was conducted. The survey included 101 families in 68 houses, consisting of 501 individuals living in various neighbourhoods throughout Basra city. The survey aims were to determine:

1. customers' general knowledge of the power shortage crisis and the available alternatives
2. customers' willingness to collaborate to solve power shortages
3. the upper and lower power requirements limits per household
4. the types and number of appliances per household to better profile domestic demand.
5. basic family, dwelling details and power consumption in accordance with family size.

The survey informed on the minimum QoE bounds that the solution must meet and provided a detailed mapping of the plethora of appliances the solution must orchestrate.



اعمار العراق وتنميته واجب على كل مواطن فيه كل من موقعه .... فخير الناس من نفع اهله ووطنه

استبيان ادارة استهلاك الطاقة الكهربائية
Demand-Side Management Measures Survey
Date: 19th January 2013
جزء من بحث الدكتوراه الجاري في جامعة ستراثكلايد – كلاسكو في بريطانيا
اسم الباحث: قاسم السالم
مدرس مهندس في قسم علوم الحاسبات – كلية العلوم – جامعة البصرة
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University of
Strathclyde
Engineering
Glasgow – Scotland – UK

ملاحظات مهمة

- لايتم كتابة اسماء الاسرة ولاعنوانها و لا ارقام هواتفها او اي معلومة تدل عليها.
- هذا الاستبيان هو جزء من متطلبات دراسة الدكتوراه في هندسة انظمة السيطرة بالكومبيوتر
- جميع المعلومات المجموعة هنا هي للاغراض الدراسية والاحصائية فقط الغرض منها توجيه الدراسة في الوجهة الصحيحة وتصميم الانظمة الالكترونية والبرمجية بما يضمن راحة المواطن.
- يهدف البحث الى معرفة اولويات المواطن وحاجاته ومدى موافقته على ما تم اقتراحه من طرق واساليب وتحليل المطروح منها لضمان رضاه.

هدف البحث
يهدف البحث الى توفير الكهرباء بصورة مستمرة الى المواطن عن طريق معرفة قدرات التوليد الحالية ومعرفة الاجهزة التي يستعملها المواطن ومدى استهلاكها للكهرباء وعددها لدراسة انماط استخدامها وكيفية توفير الكهرباء لها

ماذا تفضل؟

اجب على الاسئله الاتيه بوضع اشارة ☒ في العمود المناسب	نعم	لا	لاادري
• هل تستحسن ادخال التقنيه الحديثه الى الخدمات في العراق وانجاح البحث المقدمه في هذا المجال			
• هل انت مستعد للتعاون من اجل الحصول على الكهرباء بصورة مستمرة لمنزلك وطول السنه			
• هل انت مستعد لاستخدام بعض الاجهزة (مثل الغسالات) خارج اوقات الذروة			
• هل انت مستعد لتقليل عدد الاجهزة الكهربائيه من اجل الحصول على كهرباء مستمرة			
• هل يناسبك ان تحصل على كهرباء مستمرة كافيه لتشغيل كافه الانارة والمراوح والتلفزيون واللابتوب ومكيف واحد صيفا والانارة والمراوح والتلفزيون واللابتوب وسخان المياه شتاءا			
• هل تفضل نصب اجهزة مراقبه استهلاك الطاقه في منزلك من اجل مساعدتك في ترشيد الاستهلاك			
• هل لديك معلومات عن مصادر الطاقه المستدامه (الشمسيه والرياح والامواج ووقود القابلت ...الخ)			
• هل تريد نصب اجهزة توليد الكهرباء من الطاقه الشمسيه في منزلك او في مدينتك			
• هل تفضل ان ترشد استهلاكك للطاقه الكهربائيه حتى تكفي الكهرباء الجميع			
• هل تحب ان تشارك في تقليل اثر انبعاث الغازات التي تسبب ظاهرة الاحتباس الحراري وتغير مناخ الارض			

اجب على الاسئله الاتيه وحدد العدد او الكميه	العدد
كم امبير تسحب من مولدة المنطقه صيفا	
كم امبير تسحب من مولدة المنطقه شتاءا	
كم امبير تتمنى ان تحصل عليها كحد ادنى وبصورة مستمرة صيفا	
كم امبير تتمنى ان تحصل عليها كحد ادنى وبصورة مستمرة شتاءا	
هل لديك مولدة تعمل بالديزل، اذا كان الجواب نعم اكتب سعتها (كم امبير)	
اذا لم يكن لديك مولدة تعمل بالديزل فهل لديك مولدة تعمل بالبنزين، اذا كان الجواب نعم اكتب سعتها (كم امبير)	
هل لديك عاكس مع بطارية، اذا كان الجواب نعم ما حجم العاكس (كم امبير)	
هل لديك منظومة للطاقه الشمسيه، اذا كان الجواب نعم فكم سعتها (كم امبير)	
المنزل	
هل المنزل مؤجر	
هل لديك مولدة تكفي جميع احتياجاتك في الصيف	
عدد الغرف الكلية مع الحمامات والمطابخ (ماعدا المرافق)	
عدد المطابخ	
عدد غرف الضيوف	

Page 1 of 2

اعمار العراق وتنميته واجب على كل مواطن فيه كل من موقعه .... فخير الناس من نفع اهله ووطنه

عدد غرف الجلوس (الهول)	
عدد غرف المنام (بدون حمام خاص بالغرفه)	
عدد غرف المنام الماستر(غرفه نوم مع حمام مرفق بها)	
عدد الحمامات	
الاسرة	
عدد الافراد الكلي في البيت	
عدد الاسر في البيت	
اعلى شهادة في العائله	
عدد المسنين (رجال ونساء) في البيت (اكبر من 60 سنه)	
عدد الرجال اكبر من 18 واقل من 60 سنه العاملين في الدولة	
عددالرجال(اكبرمن18واقل من60سنه)العاملين في القطاع الخاص	
عددالنساء (اكبر من 18 واقل من 60 سنه) العاملات في الدولة	
عدد النساء (اكبر من18 واقل من60 سنه) من ربات البيوت	
عدد الشباب من الذكور في البيت (اكبر من 12 ولغايه 18 سنه)	
عدد الشباب من الاناث في البيت (اكبر من 12 ولغايه 18 سنه)	
عدد الصغار في البيت (اكبر من 3 سنوات ولغايه 12 سنه)	
عدد الاطفال والرضع في البيت (اقل من 3 سنوات)	

ت	اسم الجهاز البيتي	اشر ب(☒) الاجهزة التي تعمل باستمرار في بيتك	عدد الاجهزة في البيت	اسم الغرفه التي فيها الجهاز	اشر ب(☒) الاجهزةالاكثر الاهميةلاسرتك	عدد الاجهزة التي تخطط لشرائها مستقبلا
1	عدد الطباخات الكهربائية					
2	عدد الثلاجات الكهربائية					
3	عدد المجمدات					
4	عدد غسالات الملابس الكهربائية					
5	عدد غسالات الصحون الكهربائية					
6	عدد التلفزيونات					
7	عدد المدفئات الكهربائية					
8	عدد سخانات المياه الكهربائية					
9	عدد المكيفات					
10	عدد مبردات الهواء					
11	عدد المراوح السقفية					
12	عدد المراوح المنضدية					
13	عدد المصابيح الكهربائية الاقتصادية					
14	عدد المصابيح الكهربائية العادية					
15	عدد الشمعات الكهربائية (الفلورسنات)					
16	عدد الحاسبات المكتبية المنضدية PC					
17	عدد اللابتوبات					
18	عدد اجهزة الطبخ الكهربائية (ست البيت)					
19	عدد الاجهزة الصوتية					
20	عدداجهزةالالعاب(بلي ستيشن واكس بوكس)					
21	عدد مجففات الشعر					
22	عدد احواض الاسماك					
23	عدد الافران الكهربائية					

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Figure 5.12: Sample of the customer survey (in Arabic).

5.7 Major Findings

The survey created a profile of the local power consumption, considering a number of factors.

5.7.1 People Awareness

This part of the survey tried to reveal the awareness of people of power-related issues and to what extent they are willing to co-operate (Figure 5.13):

- **Adoption of modern technology:** 90% of the polled group were comfortable with introducing modern technologies into their daily routines, highlighting the potential for implementing new control and management solutions to mitigate severe power shortage.
- **Renewable energy sources and their importance**: slightly more than half of the polled population (54%) confirmed awareness of renewables, highlighting the need for educating people through campaigns that encourage investment in domestic renewable energy resources
- **Solar power and its uses:** (especially given Iraq enjoys nearly all-year sunshine) 71% confirmed knowledge of renewables
- **Global Warming:** 81% confirmed knowledge of this phenomenon

These results emphasises the need for comprehensive electricity-related awareness campaigns aimed at educating people about the causes of power shortages, current challenges, excessive and wasteful energy usage, alternative energy resources, and energy management techniques. Such campaigns are central and must precede any solutions in order to ensure increased levels of success through mutual cooperation.

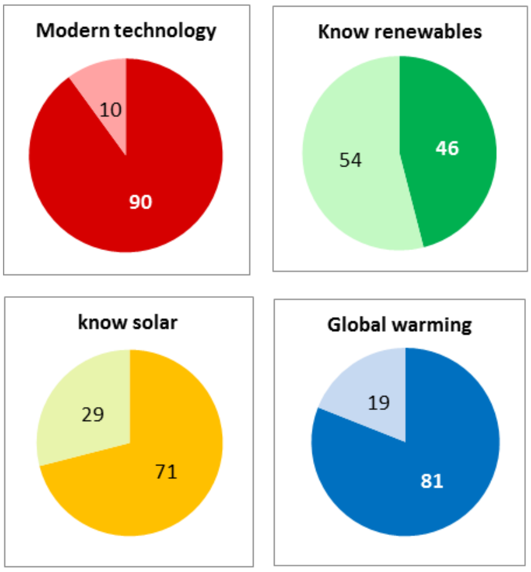


Figure 5.13: People awareness trends.

5.7.2 People Readiness

The survey probed the willingness of people to participate in power shortage mitigation projects, solutions, and initiatives and reveals a promising trend to collaborate (Figure 5.14):

- 91% would cooperate to reduce their demand in general
- 69% are ready to accept measures that shift their demand from peak hours to off-peak ones. The main cause of refusal is concern about the interference of such core operations with their work or daily schedules. Proper explanation and demonstration of the impact of domestic demand shift helps to calm such reservations.
- 74% showed a willingness to use the minimum number of appliances as a measure to reduce overall demand
- 75% were amenable to the installation of a power data logger to monitor their consumption
- 96% were aware of the importance of rationing their demand as a measure to mitigate cyclic blackouts

The readiness of people to ration their power consumption, to cooperate in order to reduce the overall demand and to manage demand and supply are consistently high. The remaining observations are a consequence of the tendency of people to protect their privacy (installing data loggers), keeping a margin of freedom in scheduling their appliance usage (shifting loads), and finally the fear of losing their freedom in using the appliance they want (minimum appliances).

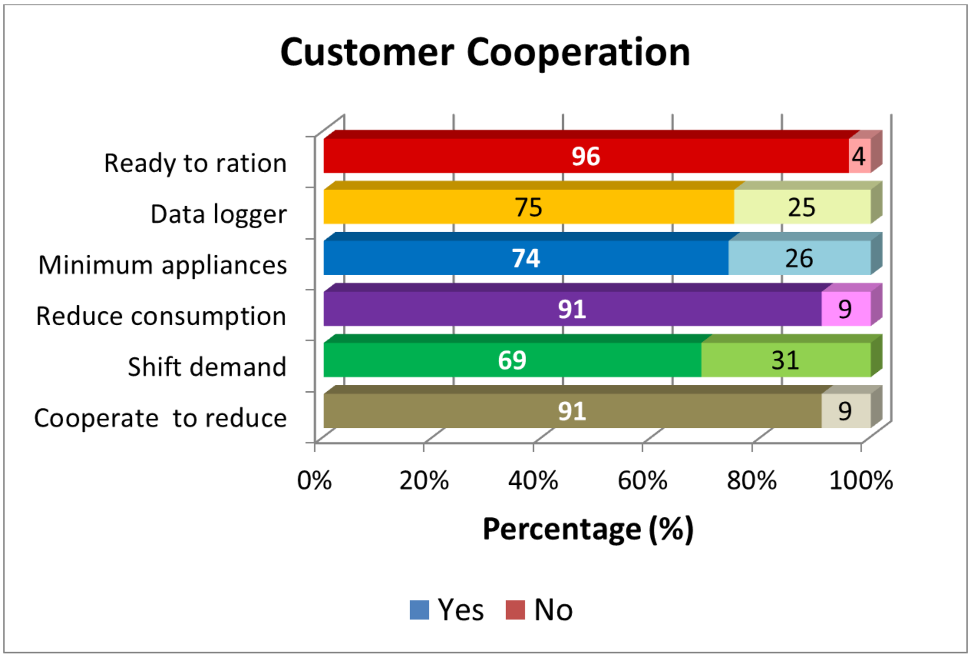
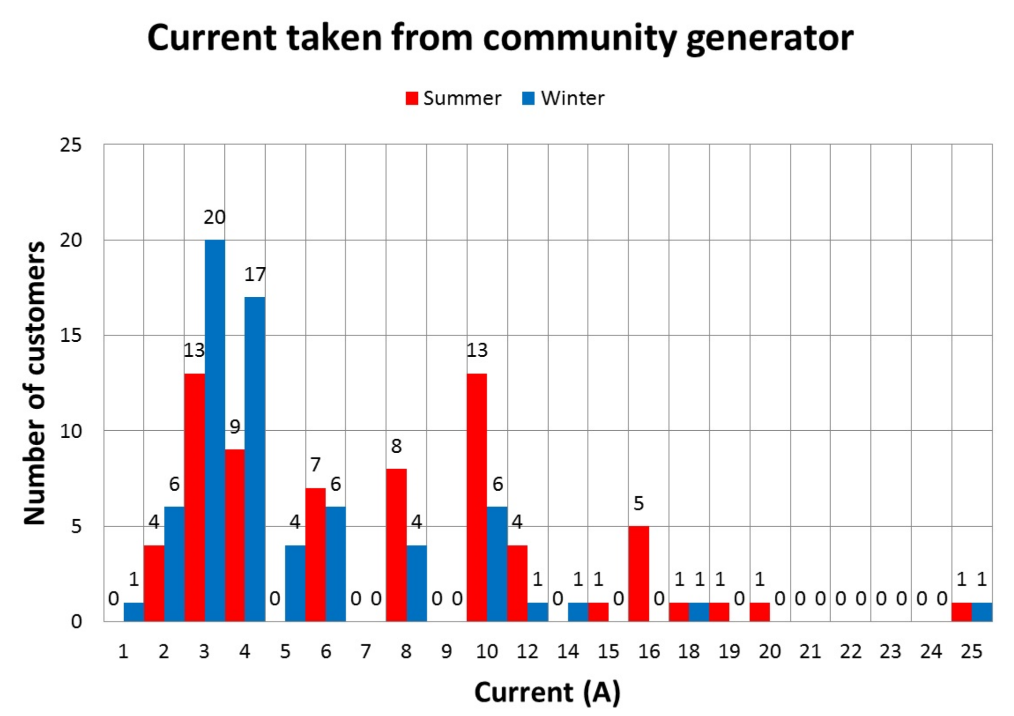


Figure 5.14: Customer trends and views.

5.7.3 Consumption

Detailed electricity consumption is mapped to establish a more granular understanding of the main contributors to the overall power demand. The mapping concentrated on categorising the demand of each family according to its power consumption obtained from community generators. Since these generation facilities are commercial and their prices are high, each family will buy a minimum amount of power sufficient to meet their basic needs, a valid indication of a true minimum power requirement of each family. Figure 5.15 shows the current drawn from community generators for each family (or groups of families living in the same house); nearly half the polled population (37 houses) draw 3-4 A in winter to cover demand, the number shrinks to 22 houses in summer, since some upgrade their power purchase to higher currents in order to operate air conditioning systems.



Notes:
1. Numbers above columns are the number of households buying that amount of current.
2. Number of households in summer and winter for the same current value are not related to each other.

Figure 5.15: Normal consumption by surveyed participants in summer and winter.

The mapping also revealed a sizeable difference between the power people buy and what they wish to consume. Table 5.3 shows these power limits in both winter and summer i.e. 3 A -120 A (0.66 kW – 24 kW) in summer, nearly fivefold greater than what they buy and between 1 A -80 A (0.22 kW – 16 kW) in winter, threefold what they actually buy.

Table 5.3: Sample survey results showing minimum and maximum electric current requirements of surveyed participants in summer and winter.

Buy at summer	Buy at winter	Wish to have at summer	Wish to have at winter
Min	**Min**	**Min**	**Min**
2 A	1 A	3 A	1 A
0.44 kW	0.22 kW	0.66 kW	0.22 kW
Max	**Max**	**Max**	**Max**
25 A	25 A	120 A	80 A
5.5 kW	5.5 kW	26.4 kW	17.6 kW

5.7.4 Family Size

The average electricity consumption per person is calculated assuming that the demand is generated by operating all appliances using a unified set of appliance test demand for all families, aimed at determining the maximum potential demand and its relation to the size of family (Figure 5.16).

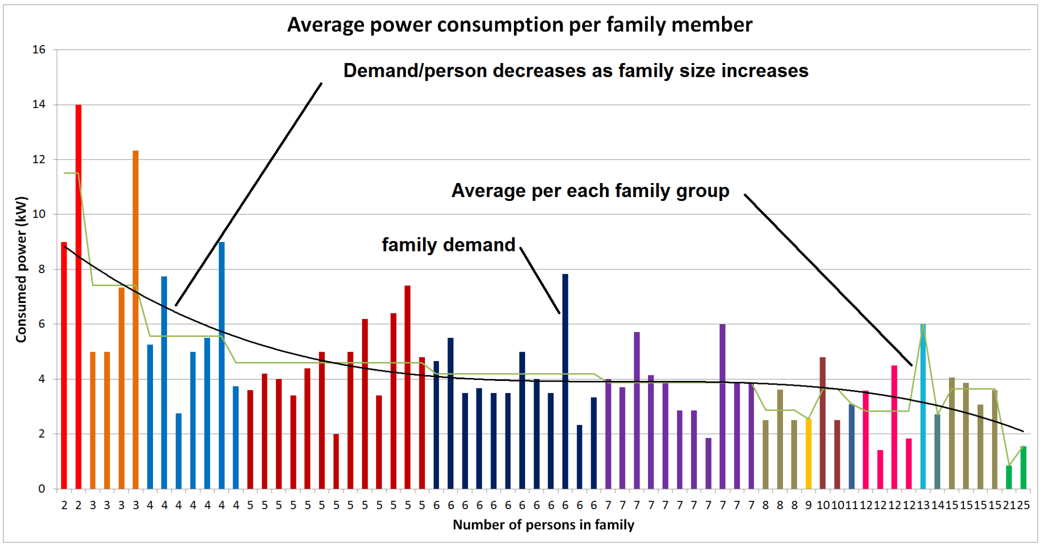


Figure 5.16: Average power consumption per capita.

The general trend shows that members of small families consume more power than in crowded families and that demand varies between families of the same size owing to differences in financial or social status e.g. many families think that acquiring more powerful appliances, especially air conditioning (including high capacity ones), reflects their social status or wealth regardless of power consumption.

5.7.5 Appliances

Figure 5.17 shows the actual appliance ownership across the area. Certain appliances such as microwave ovens, coffee makers (and their derivatives such as tea and espresso makers) and electric kettles are not routinely in use; the population uses natural gas for all cooking and hot drink preparations due to its low cost. Tumble driers are not needed due to the hot weather. Pool pumps are not included because the majority of houses do not own a swimming pool. The dish washer is rarely used with only 2% of the population owning such an appliance.

As expected lighting equipment is used in large numbers, while air conditioning appliances and various types of fans are popular due to the hot weather. Electric ovens and cookers are used mainly as backup in case of a disruption in the natural gas supply and thus are not used on a daily basis. 39% of families own COs in addition to their air conditioning systems, a fact worthy of consideration in developing power shortage mitigation strategies.

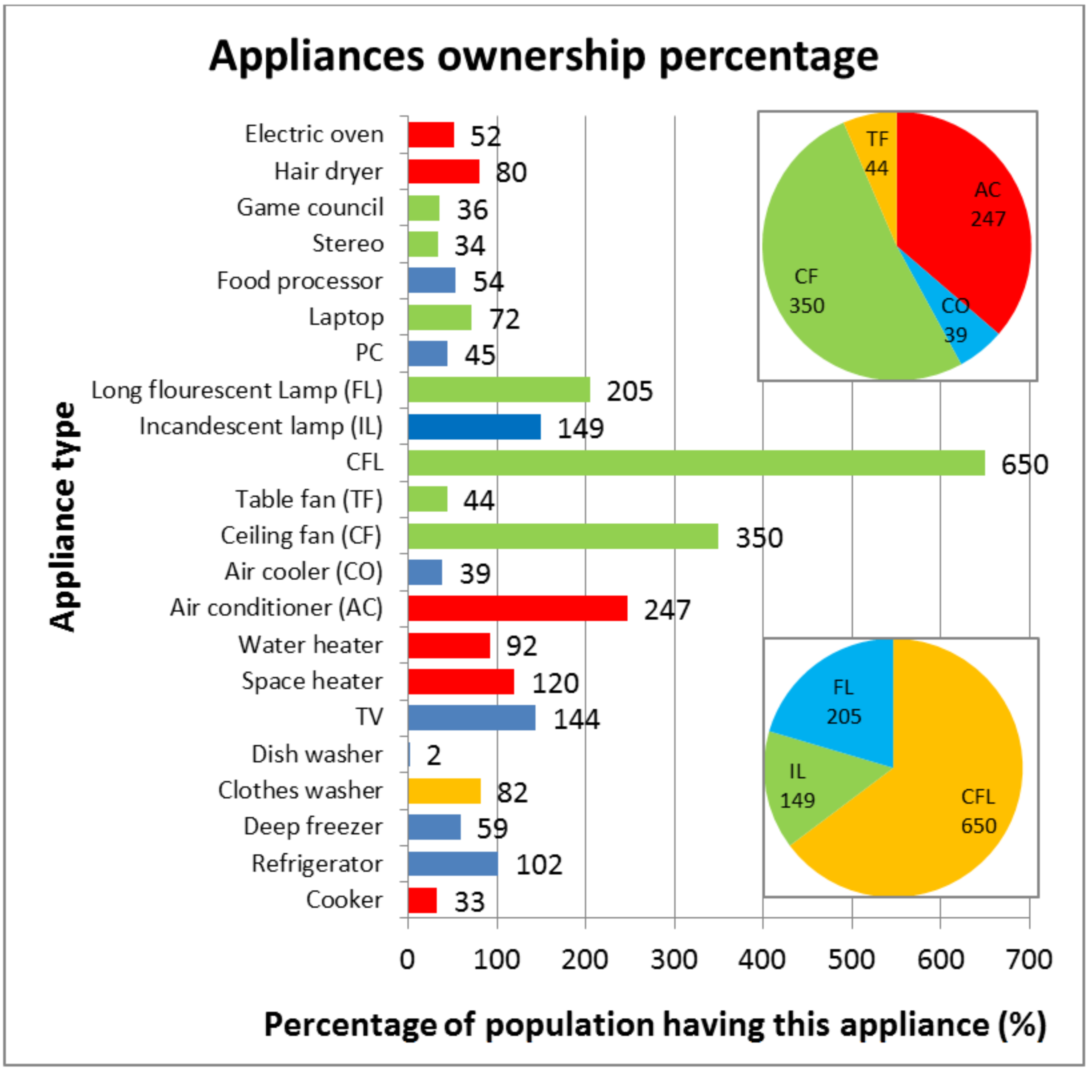


Figure 5.17: Appliance ownership percentages.

5.7.6 Domestic Generation

The domestic generation is mapped and the results are summarised in Figure 5.18. 50% of the houses own a gasoline and 18% have diesel powered domestic generators. In addition, only 1% owns a solar system (one house only has a 100 W PV system) and 3% have a battery storage system for power charging and inversion. 28% of the houses do not possess any type of domestic generation.

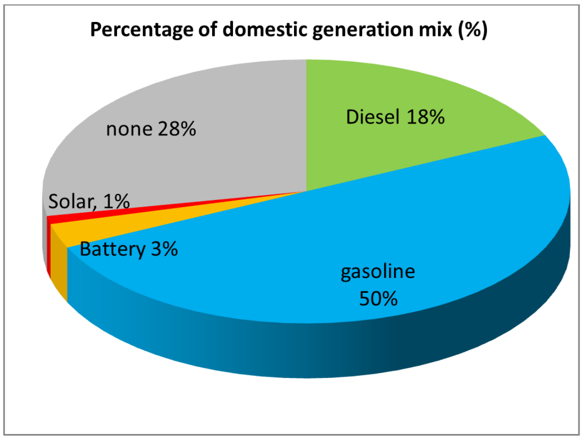


Figure 5.18: Sample survey results showing the mix of domestic generation.

5.8 The Test Sample

For the purposes of developing the final implementation and evaluation of the proposed cyclic blackout mitigation system, a sample of 20 dwellings housing 20 families are selected, shown in Figure 5.19 marked by the yellow rectangle. Figure 5.20 shows further detail of these houses, their LV distribution transformer, local community generator, local landmarks and the local substation.

Figure 5.19: The 20 house test sample.

The permission of the owners of these houses was obtained and these 20 houses will be used in the development of a proof-of-concept implementation, to be expanded to include the entire Kafaat neighbourhood, upon validation of the proposed cyclic blackout mitigation strategy. The long term aim of the solution is to be able to manage all residential quarters in Basra city.

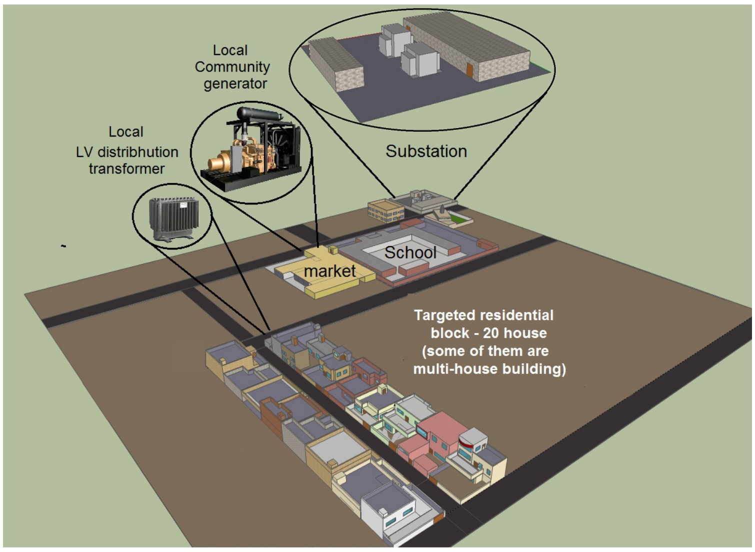


Figure 5.20: 3D feature plot of the selected 20 houses.

5.9 Summary

The residential quarter ‘Kafaat’ in Basra, Iraq was selected as a use case for the development and evaluation of the proposed cyclic blackout mitigation strategy. A field survey was undertaken to map the environment, its inhabitants, power consumptions profiles and available standby generation. The conclusions of the study are the following:

1. considerable amount of unused or underutilised standby generation exist within Kafaat and its surroundings. Mobilizing these generation assets is a promising approach that can make a difference in covering local demand.
2. modern Iraqi uninsulated houses built from concrete and iron are less efficient than older well-insulated dwellings built using natural materials. Enhancing architectural designs is a factor in solving its severe and chronic power shortages.
3. consumers have shown a good degree of understanding of the challenges of power shortages and a strong willingness to co-operation to ensure that any solution is effective. Nevertheless awareness campaigns are still needed to increase the level of participation.
4. large families consume less power (per capita) than smaller ones mostly due to social behaviours
5. nearly half the inhabitants purchase a very low amount of power (as low as 0.66 kW) to cover their demand due to cost
6. due to the availability of natural gas and coupled to the hot weather, the majority of high power consumption appliances such as ovens and driers are not in routine use throughout Kafaat. The most significant power usage is due to air conditioning systems.
7. air coolers are available in significant numbers, and represent a promising potential option in any power management strategy aimed at mitigating cyclic blackouts
8. domestic renewable systems are rare in Kafaat; incentives aimed at promoting the deployment of such systems under suitable management form a promising approach.
9. not all families possess local domestic generation. Gasoline generators dominate despite their short working periods and low power production.

Chapter Six
The Integrated Development Environment

6.1 Preface

In this chapter, a software platform to aid in the design, execution, and validation of the proposed cyclic blackout mitigation strategies is described. The main features, modules, GUI, and operations of the Integrated Development Environment (IDE) are explained. The details of an Abstract Residential Demand Generator (ARDG), its principle of operation, and structure are introduced. The ARDG is the core source of input data for developing and evaluating demand management strategies. The validation of the IDEA is presented through a series of tests.

6.2 DDSM-IDEA

Real-life implementations of wide-scale, advanced solutions during development phases are often not feasible due to the need for a substantial amount of investment and a dedicated support team of qualified personnel. Some projects have other requirements such as people interaction; control of a large population of instruments, such as appliances; an extensive environment and highly interconnected subsystems. Software development environments are thus a practical and often effective alternative to development cycles, leaving the real-life implementation to the final phase of such projects. For the purposes of the research, a dedicated Distributed Demand Side Management - Integrated Development Environment with Agent support was designed and implemented in Matlab®. The aim is to provide a user-friendly flexible platform equipped with all necessary functions to develop and evaluate agent-based power management strategies targeting the residential sector. The platform should have the ability to incorporate supply side participation as well as demand side in any solution, supported by a thorough, fine-tuned residential load emulation scheme used as a test community for the application.

6.2.1 DDSM-IDEA Principles

The DDSM-IDEA can be considered as an interface between four main elements; a population of houses and appliances; a generation mix; DDSM management strategy; and its users. Figure 6.1 shows these parts and their interconnection through the DDSM-IDEA.

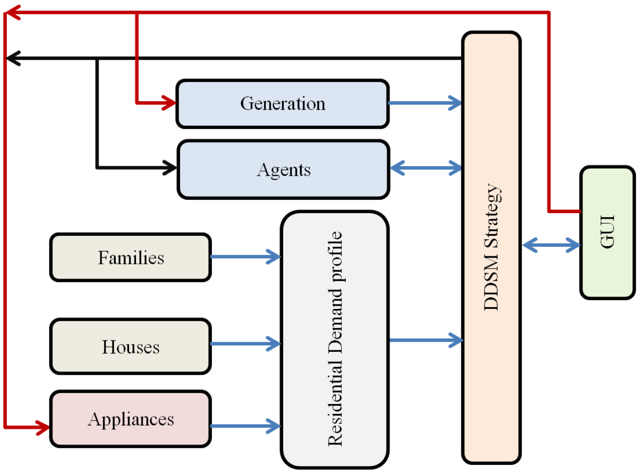


Figure 6.1: General block diagram of the DDSM-IDEA platform.

6.2.2 The Framework

A robust plug-and-play framework acting as a development environment for DSM strategies and operations is core to the DDSM-IDEA, comprising various functions essential to the development of strategies and supporting basic types of agents with the necessary graphics plotting functions. The proposed strategies and agents can be added easily and used directly.

6.2.3 The Graphical User Interface

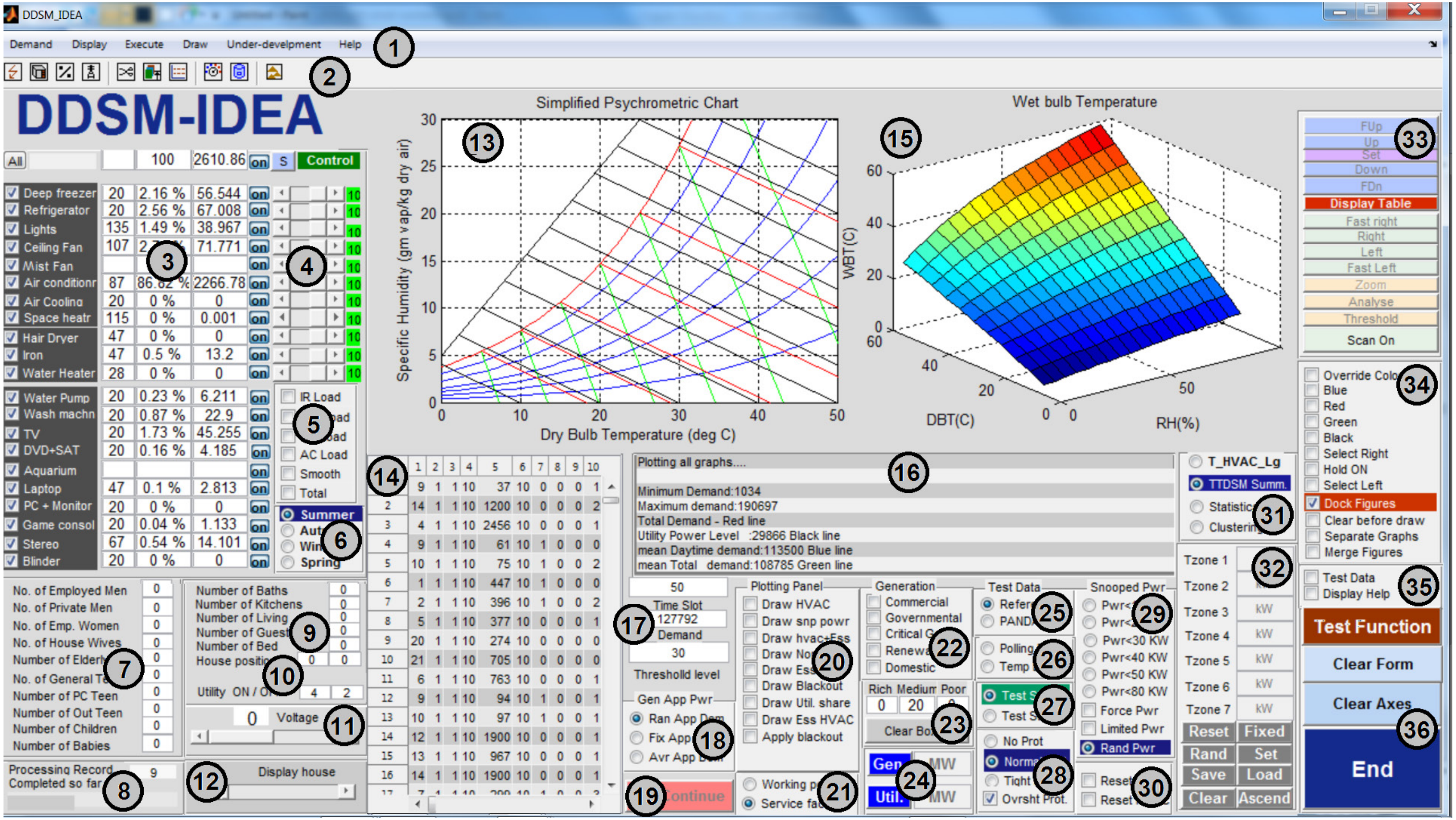
The DDSM-IDEA, a useful platform designed for planners and system designers to develop evolution scenarios and verify strategies prior to field implementation, has an all-in-one single screen cockpit-like programmer-oriented GUI (Figure 6.2) i.e. all operations are grouped in one screen and can be operated in any desirable 'logical and permissible' sequence. This type of arrangement eliminates the need for searching for buttons, operations, messages, settings, results, and graphs. The DDSM-IDEA's GUI has the following advantages:

- reduces the time needed to master platform usage
- makes 'immature code' test operations easier
- makes debugging software problems more direct
- enables total demand disintegration possible.
- enables detailed load analysis operations.
- makes comparisons of graphical results, tabular data, and received message information straightforward.

The GUI is designed with the intention of embedding all capabilities needed to make the power management strategy programming easier by providing a range of necessary functionalities such as:

- code test buttons
- dual-graphics display for parallel output and graph comparisons
- tabular data briefing area
- slider and window type progress indicators
- graphics display control
- resource selection and change mechanisms
- manual setting with single-set saving and loading capabilities of popular settings; randomising and fixing; setting and re-setting of certain parameters, reducing development time.

In addition, the DDSM-IDEA has a two level help system, the first is a tool tip help that explains the purpose of some of the buttons displayed and the other is brief explanatory messages of certain operations. The platform is designed with the aim of providing users with an IDE that can be used in the rapid development of extensive residential power management strategies.



☑						
			100	2610.86	on	
☑	Deep freezer	20	2.16 %	56.544	on	10
☑	Refrigerator	20	2.56 %	67.008	on	10
☑	Lights	135	1.49 %	38.967	on	10
☑	Ceiling Fan	107	[illegible]	71.771	on	10
☑	Mist Fan				on	10
☑	Air conditionr	87	86.82 %	2266.78	on	10
☑	Air Cooling	20	0 %	0	on	10
☑	Space heatr	115	0 %	0.001	on	10
☑	Hair Dryer	47	0 %	0	on	10
☑	Iron	47	0.5 %	13.2	on	10
☑	Water Heater	28	0 %	0	on	10
☑	Water Pump	20	0.23 %	6.211	on	
☑	Wash machn	20	0.87 %	22.9	on	
☑	TV	20	1.73 %	45.255	on	
☑	DVD+SAT	20	0.16 %	4.185	on	
☑	Aquarium				on	
☑	Laptop	47	0.1 %	2.813	on	
☑	PC + Monitor	20	0 %	0	on	
☑	Game consol	20	0.04 %	1.133	on	
☑	Stereo	67	0.54 %	14.101	on	
☑	Blinder	20	0 %	0	on	

☐ IR Load
☐ AC Load
☐ Smooth
☐ Total

● Summer
○ Aut
○ Win
○ Spring

No. of Employed Men	0
No. of Private Men	0
No. of Emp. Women	0
No. of House Wives	0
Number of Elderly	0
No. of General T	0
Number of PC Teen	0
Number of Out Teen	0
Number of Children	0
Number of Babies	0

Number of Baths	0	
Number of Kitchens	0	
Number of Living	0	
Number of Guest	0	
Number of Bed	0	
House positi	0	0
Utility ON / O	4	2

Voltage 0

Processing Record 9
Completed so far

	1	2	3	4	5	6	7	8	9	10
	9	1	1	10	37	10	0	0	0	1
2	14	1	1	10	1200	10	0	0	0	2
3	4	1	1	10	2456	10	0	0	0	1
4	9	1	1	10	61	10	1	0	0	0
5	10	1	1	10	75	10	1	0	0	2
6	1	1	1	10	447	10	1	0	0	0
7	2	1	1	10	396	10	1	0	0	2
8	5	1	1	10	377	10	0	0	0	1
9	20	1	1	10	274	10	0	0	0	0
10	21	1	1	10	705	10	0	0	0	0
11	6	1	1	10	763	10	0	0	0	1
12	9	1	1	10	94	10	1	0	0	1
13	10	1	1	10	97	10	1	0	0	1
14	12	1	1	10	1900	10	0	0	0	1
15	13	1	1	10	967	10	0	0	0	1
16	14	1	1	10	1900	10	0	0	0	1

```
Plotting all graphs....

Minimum Demand:1034
Maximum demand:190697
Total Demand - Red line
Utility Power Level  :29866 Black line
mean Daytime demand:113500 Blue line
mean Total   demand:108785 Green line
```

○ T_HVAC_Lg
● TTDSM Summ.
○ Statistic
○ Clustering

50
Time Slot
127792
Demand
30
Threshold level

Gen App Pwr
● Ran App Dem
○ Fix App
○ Avr App Dem

Plotting Panel
☐ Draw HVAC
☐ Draw snp powr
☐ Draw hvac+Ess
☐ Draw No
☐ Draw Ess
☐ Draw Blackout
☐ Draw Util. share
☐ Draw Ess HVAC
☐ Apply blackout

○ Working p
● Service fa

Generation
☐ Commercial
☐ Governmental
☐ Critical G
☐ Renewa
☐ Domestic

Rich	Medium	Poor
0	20	0

Test Data
● Refer
○ PAND

○ Polling
○ Temp

● Test S
○ Test S

○ No Prot
● Norma
○ Tight
☑ Ovrsht Prot.

Snooped Pwr
○ Pwr<
○ Pwr<
○ Pwr<30 KW
○ Pwr<40 KW
○ Pwr<50 KW
○ Pwr<80 KW
☐ Force Pwr
☐ Limited Pwr
● Rand Pwr

☐ Reset
☐ Reset

☐ Override Colo
☐ Blue
☐ Red
☐ Green
☐ Black
☐ Select Right
☐ Hold ON
☐ Select Left
☑ Dock Figures
☐ Clear before draw
☐ Separate Graphs
☐ Merge Figures

☐ Test Data
☐ Display Help

Figure 6.2: The DDSM-IDEA graphical user interface.

6.2.4 The DDSM-IDEA GUI Controls

The DDSM-IDEA has tools that enable the control of multi attributes in the simulated environment:

1. **Main menu:** utilised to trigger main operations such as generating and analysing residential demand, displaying total, single house, or various appliance demands, launch power management strategies, and draw various outputs. Some of the menu items are placeholders for future operations.
2. **Main toolbar:** used as a fast launch mechanism for frequently used functionalities during strategy development and programming such as analysing the total demand and identifying the appliances contributing to it; drawing utility power during normal and cyclic blackout episodes; plotting various demand curves such as total, basic set, water heater, air conditioning, space heating in isolation, or in combination, if applicable.
3. **Appliance briefing panel**: displays essential appliance population information in the residential demand profile. The displayed information includes the number of appliances, their total demand, and their contribution to the overall residential demand. The same panel is used also to display the information for a certain point on the overall demand profile, typically used for demand curve inspection and checking.
4. **Appliance control panel:** holds the appliance ON/OFF buttons and their thermostatic sliders, useful in preferentially excluding certain appliances to investigate their impact on the overall demand and to set the thermostats of certain appliances. This functionality is useful in trialling a DSM measure manually, prior to full programming and implementation. Lights are assumed to have dimmers.
5. **Total and HVAC demand plotting panel:** to plot certain combinations of the total, various HVAC demand curves and smoothed [63] total demand

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[63] Total demand smoothing using moving average method used in one of the previous trials in one of the earlier versions of the developed strategy. It is kept for future use.

6. **Season selection panel:** to select the season for the residential demand profile generation process e.g. the decision to incorporate HVAC appliances is made at this stage.
7. **Family details panel:** to display the mix of people and their occupation for each family during overall demand profile browsing.
8. **Processing record indicator:** an indicator used to track the progress of the demand generation process.
9. **House details panel:** to display number and type of rooms in each dwelling during overall demand profile browsing.
10. **Cyclic blackout setting control:** to set the ON/OFF periods of a cyclic blackout.
11. **Voltage reduction slider:** to reduce overall voltage to check its effect on the generated overall demand.[64]
12. **House number:** displays the sequence number of the house currently being displayed during various demand management operations.
13. **Graphics display1:** 2D/3D display normally used for the visualisation of results.
14. **Tabular data briefing panel:** to display data from tables for checking purposes; certain tables can be displayed from the GUI and the rest can be generated from within the programmed DDSM management strategy.
15. **Graphics display2:** 2D/3D display normally used for the display of results.
16. **Message panel:** for displaying text messages, warnings, summaries, help text, parameter values and progress indicators.
17. **Total demand analysis pointer readings:** a three box display visualising a selected time period for demand analysis, the amount of demand at the chosen time period, and the threshold level for referencing.
18. **Appliance demand category setting panel:** to select the appliance demand of all appliances within a certain residential demand profile; the DDSM-IDEA

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[64] Used to simulate and test the effect of brownouts on the overall demand during future demand management experimentation.

offers three power consumption levels for each appliance i.e. minimum, maximum, and average. These values are chosen from a pre-stored appliance demand database that has these three values for each appliance.

19. **Acknowledgement button:** to issue an acknowledgement in case of any alert messages. It can also be used as an inter-stage temporary pause mechanism in a multi-stage operation.
20. **Multi-graph plotting selection panel:** controls the selection of graphs to be plotted, which may include one or more of the following; HVADC demand, essential demand, normal (total) demand, snooped power, HVAC plus essential demand, utility during a cyclic blackout, and the utility (nationwide) share for the targeted population.
21. **Service factor setting panel:** controls the manner in which the overall demand is managed during cyclic blackout prevention operations. The first control sets the ‘working period’ which instructs the management strategy to shed the load of ACs that have been working for the longest period of time and are nominated to be replaced with COs, while the second control instructs the management strategy to replace ACs that serve less people with COs, leaving the rest operational.
22. **Generation selection panel**: controls the selection of sources of generation participating in the process including community (commercial), critical (hospital), government (public), domestic, and available renewables[65].
23. **Socio-economic population mix selection panel:** to set the combination of rich/medium/poor families, the difference between each type is reflected in the house size and the demand of the used appliances.
24. **Utility/Generation level setting panel:** hosts two controls used to set the amount of utility/generation power levels in MW. The first is used during cyclic blackout prevention demand management operations to set the available utility level, while the second is for future use.

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[65] Added for future use.

25. **Test data panel:** to switch the test data set during the power management strategy development phase between a reference set and a set from the generated residential neighbourhood.
26. **HVAC distribution principle selection panel:** to select the manner in which the ACs are switched. Two options are provided: the first is through interlocking all HVACs for the same amount of time i.e. interlocking for ‘x’ minutes, while in the other, hot houses will have their ACs operational while cooler dwellings are allowed to operate their COs.
27. **Test strategy selection panel:** provides the ability to test strategies used during the development phase**.**
28. **HVAC mix demand overshoot protection panel:** hosts three controls used to check if the AC-CO interlocking strategy exceeds the maximum power limits. Three settings are possible; no protection, normal, and tight protection, the difference between levels being equal to the difference between the real load and the surplus power level. The first permits the resulting AC-CO-MF combination from exceeding its allocated demand ‘occasionally’ by few Watts. In the second, only the demand of ACs is taken into consideration when preventing such a condition. Finally, both the demand of ACs and COs (or COs and MFs) demand is considered and the best protection against such cases is provided. It is worth mentioning that as more protection is exercised, the more unallocated power is generated, which means that less ACs and more COs (or less COs and more MFs) are allocated. Selecting the right protection level is crucial since it determines the balance between offering the largest AC coverage and generating the least unused power.
29. **Snooped power maximum limit setting panel:** sets the desirable maximum level of available (surplus) power. The panel allows the setting of a maximum and another two controls, one to force the DDSM-IDEA to switch to a manual power setting, while the other is used to activate/deactivate the limit in the maximum of the randomly generated surplus power.
30. **Basic set/HVAC demand inclusion/exclusion panel:** to exclude the basic set

or HVAC demand from the overall demand in power management strategy development, highlighting the impact of such demand on the overall profile.

31. **Table display selection:** to select the data table to display during development phases only; the list of displayed tables can be updated to indicate the most relevant.
32. **Surplus power manual setting panel:** to impose manual power supply level settings during a day after segmenting into seven time zones, overriding any available type and amount of generation. This is used only for testing purposes during development phases. This panel has several buttons to save the selected power levels i.e. reset to zero, clear, generate power level randomly, assign fixed power levels, or set sorted levels of power.
33. **Total demand analysis panel:** also referred to as the 'demand scanner' (Figure 6.3), the panel is used for testing the generated demand profile for unexpected peaks, sequences, or any other striking features. This control is normally inactive and is activated by the 'Scanner ON' button. The total demand of the simulated population is displayed in 'Graphics display area2' and a variable position 'cross hair'-like lines are displayed (green and red in Figure 6.3) able to be moved in two directions (up and down for green one and left and right for the red one).

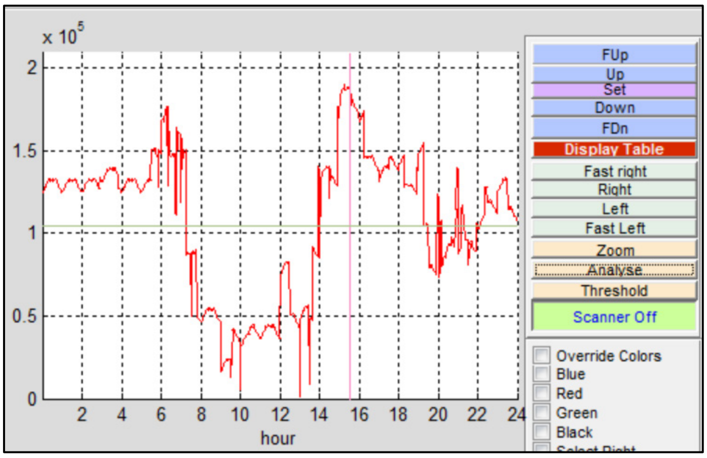


Figure 6.3: The demand scanner.

If the targeted point on the total demand curve is unclear, the scanner has a zoom capability that enlarges the demand at any selected point (Figure 6.4).

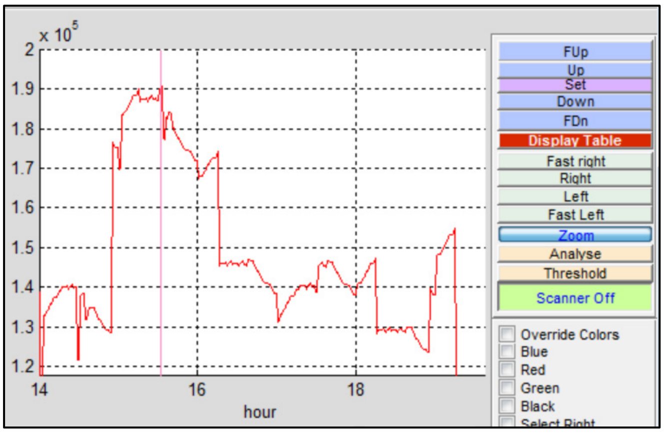
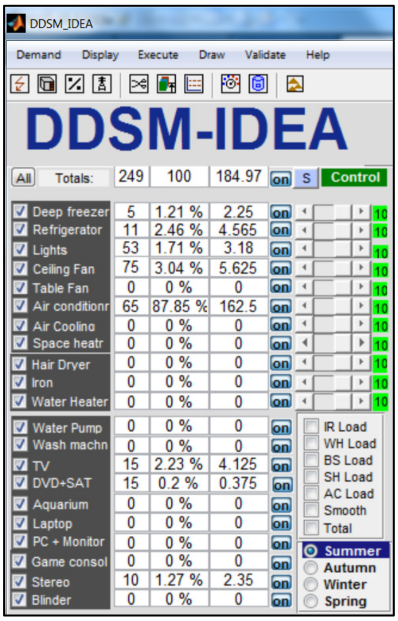


Figure 6.4: Demand zooming through the scanner.

A total demand analysis through disaggregation can be generated, the result being a list of all appliances at that moment of time participating in creating the demand. The full list of appliances, their number, demand, and percentages of the overall demand are displayed in the appliance briefing panel (Figure 6.5). Likewise, moving the threshold line (green) to any level displays the value of the total generated demand at the intersection of the threshold line with the demand.



Totals:	249	100	184.97	on	
☑ Deep freezer	5	1.21 %	2.25	on	10
☑ Refrigerator	11	2.46 %	4.565	on	10
☑ Lights	53	1.71 %	3.18	on	10
☑ Ceiling Fan	75	3.04 %	5.625	on	10
☑ Table Fan	0	0 %	0	on	10
☑ Air conditionr	65	87.85 %	162.5	on	10
☑ Air Cooling	0	0 %	0	on	10
☑ Space heatr	0	0 %	0	on	10
☑ Hair Dryer	0	0 %	0	on	10
☑ Iron	0	0 %	0	on	10
☑ Water Heater	0	0 %	0	on	10
☑ Water Pump	0	0 %	0	on	
☑ Wash machn	0	0 %	0	on	
☑ TV	15	2.23 %	4.125	on	
☑ DVD+SAT	15	0.2 %	0.375	on	
☑ Aquarium	0	0 %	0	on	
☑ Laptop	0	0 %	0	on	
☑ PC + Monitor	0	0 %	0	on	
☑ Game consol	0	0 %	0	on	
☑ Stereo	10	1.27 %	2.35	on	
☑ Blinder	0	0 %	0	on	

☐ IR Load
☐ WH Load
☐ BS Load
☐ SH Load
☐ AC Load
☐ Smooth
☐ Total

● Summer
○ Autumn
○ Winter
○ Spring

Figure 6.5: Appliance briefing panel displaying disaggregated total demand data.

34. **Graphics displays (1 & 2) control panel:** controls the display of graphs in ‘Graphic display1’ and ‘Graphic display2’, allowing the selection of colours,

merging graphs and docking/floating graphics among other things.

35. **Ancillary buttons block:** provides two ancillary functions; the first is activating test code usage (through the 'Test data panel') and the second is enabling the help display in the message area.
36. **Main buttons block:** three buttons for clearing the graphics areas, the GUI, and ending the DDSM-IDEA.

6.3 The Residential Demand

The residential demand of a single dwelling is considered to be the result of interaction between people and various household devices and appliances under the influence of several factors such as the weather, the socio-economic status, the characteristics of the targeted dwelling, appliance usage patterns, and occupancy patterns (Figure 6.6).

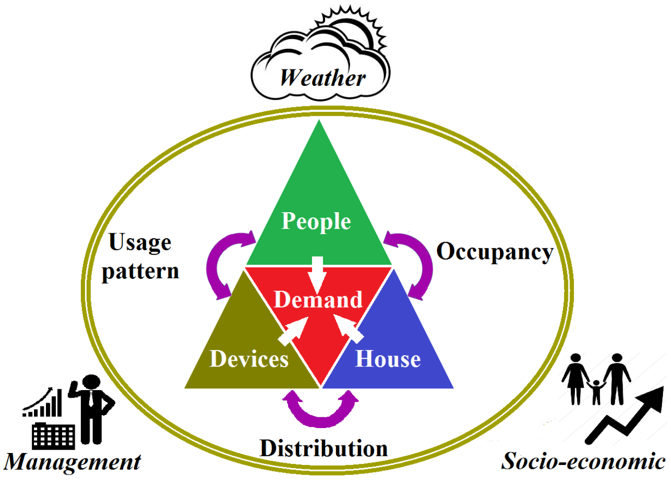


Figure 6.6: Demand generation main factors and their interaction.

The interaction of these factors produces a diversity of residential demand profiles (Figure 6.7). The end user is the main core factor in determining the profile; customer behaviour plays a crucial role in developing any methodology for generating residential demand.

By considering these factors, and in order to complete the functionalities of the DDSM-IDEA, the platform has been provided with a built-in abstract demand

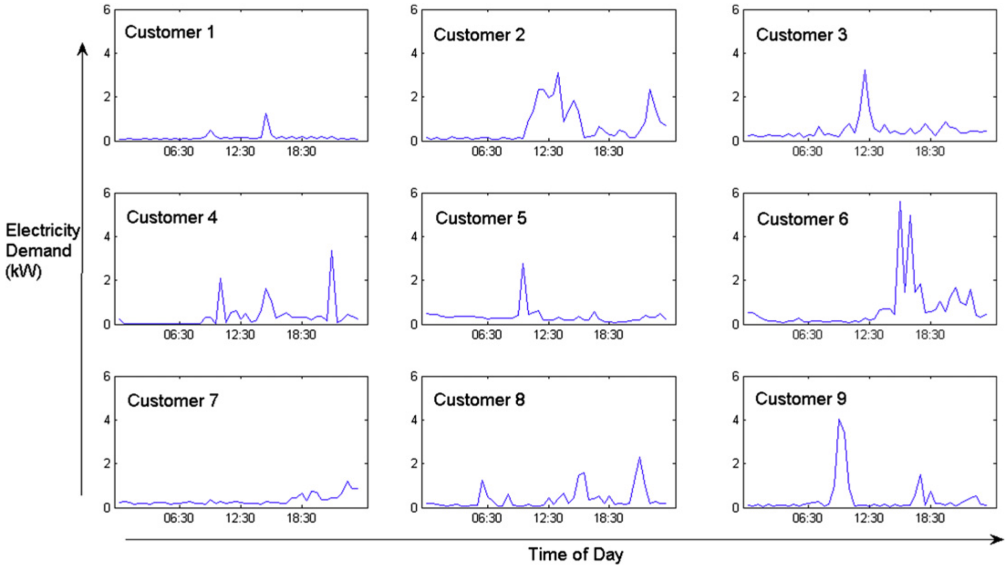


Figure 6.7: An example of a typical daily demand of 9 houses (Ireland on 1/7/2009) [229]

generation mechanism capable of generating a wide spectrum of residential demand through aggregating the demand of various appliances distributed within households.

6.3.1 The Residential Demand Generation

Residential demand is driven largely by the power consumption of a wide spectrum of electrically-powered devices, instruments, and appliances which present a mix of attributes such as price, efficiency and most importantly for this research, different power consumption. A vast diversity of residential appliance models follow similar usage patterns but at differing levels of power consumption. These differences are evident even in identical appliances distributed across consumer areas owing to age, house characteristics, appliance installation, location, weather conditions, and family structure and size. These small and large differences have complicated the process of producing a demand model that fully matches all real life scenarios and consequently any model is highly application-dependent.

The overall residential demand is shaped primarily by appliances; refrigerators and freezers produce a demand analogous to a train of pulses, while water heaters and cookers exhibit spike-like demand; continuous loads such as lights represent an offset space heating and air conditioning are significant blocks of high demand that could last for hours. Figure 6.8 shows the demand of a typical house showing some of these types of demand. The mix of appliances is largely country-dependent, hot countries differ from cold ones, and oil exporting countries have different demand from oil importing ones.

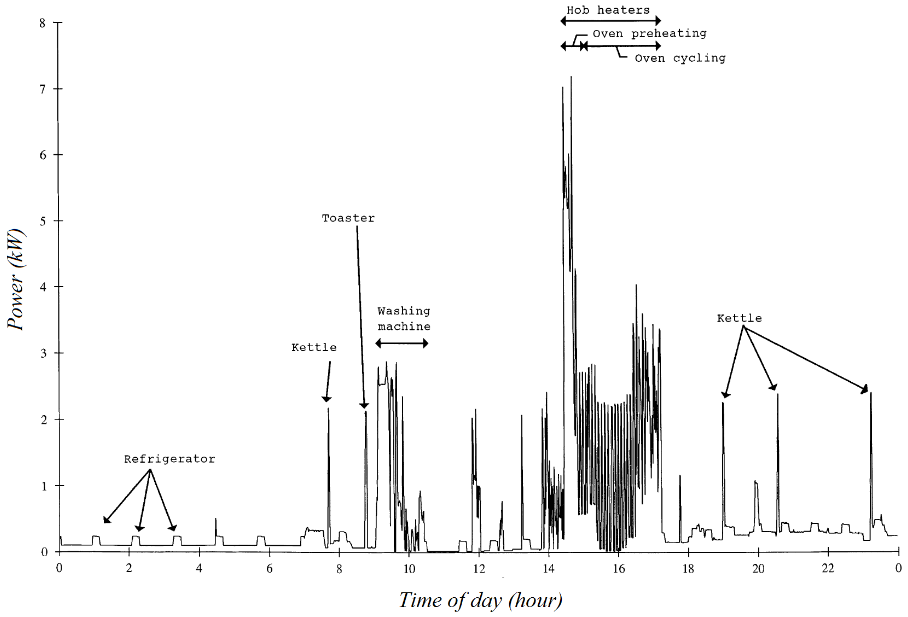


Figure 6.8: An example of a daily demand for a UK household [230].

6.3.2 The Demand Generation Mechanism

The proposed demand generation mechanism follows certain guidelines to ensure clarity in comparison with alternative approaches, expressed as a group of requirements that must be fulfilled:

1. have the ability to generate the demand of a single house
2. have the ability to produce the desired demand at a useful time granularity
3. be appliance-independent i.e. its principle must not be a function of specific appliances
4. have the ability to reflect the socio-economic differences between different families and its impact on their demand
5. have the ability to take into consideration the effect of seasonal changes
6. have the ability to generate the demand of full neighbourhoods by

aggregating the demand of single dwellings

7. must deal with appliances, their behaviour, and demand in an abstract way but represent the general behaviour common to all appliances of that type. In addition, an abstract demand shape is used to act as an envelope containing various demand profiles resulting from differences in appliance sizes, models and operating modes.

For the purposes of the research, the mechanism does not consider the following:

1. rarely used appliances such as swimming pool pumps; however they can be added if they are needed.
2. small appliances such as mobile chargers
3. every category of inhabitant e.g. ship crew who can be absent for many months from their homes
4. house structures that are rarely found such as conservatories and green houses.

6.3.3 Residential Demand Generation Overview

Residential demand contributes 16%-- 50% (nationally) and 31% (worldwide) [231] of overall energy consumption, and yet insufficient information is available to profile it. In contrast, other sectors (industrial, commercial, transportation) which are normally governed through centralized ownership, follow well-defined power consumption patterns and streams, owing to the availability of a plethora of documentation, high levels of operational experience, detailed regulations, and above all, a continuous self-interest in reducing the demand. Any energy model relies on accurate input data; the level of detail of the available input data can vary dramatically, defining the use of different modelling techniques with different strengths, weaknesses, capability, and applicability.

The process of developing a residential energy demand model requires a range of data such as family make-up; their appliances; house specifications; climate; historical data on their energy consumption; and socio-economic information such as habits and behaviours which can account for up to 100% increase in the consumption per house [232]. The amount, variety, and significance of such data differ between scenarios, which results in variation between demand models.

Two main approaches are routinely used to design demand models; top-down and bottom-up [233]. The former handles residential demand as a whole without paying any regard to individual houses, appliances, or occupants, used mainly for estimating domestic demand on the national level [231]. The latter deals with individual dwellings, appliances, and customers taking into account their inter-dependencies and interactions, aggregating their demand to produce an overall profile. Since this research requires access and full control of HVAC appliances in each dwelling, the demand generation mechanism developed is based on the bottom-up approach.

The bottom-up approach includes statistical and engineering models, the former utilises a set of appliance usage probabilities representing the likelihood of using a certain appliance at a certain instant of time calculated from historical data and compared with randomly generated numbers to determine if that appliance is used or not. This approach was not used due to the fact that there is no historical consumption data or surveys concerning the selected case study. Engineering models rely on a wide range of simple and detailed models based on house characteristics, occupant types, and appliance specifications without the need for historical data [233], whilst providing the flexibility to model newly deployed technologies and appliances. The downside of these models is their need for extensive house specifications which limits their application to a small number of well-documented areas.

In the absence of historical demand data, a demand generation technique based on the individual's daily activities and interaction with appliances is presented and used to generate an abstract residential demand that can fulfil the requirements of the research. Here 'abstract' means that the model produces a residential demand harmonious with the demand produced by other models, resembling their demand up to the possible maximum, follows their general trends, and is as close as possible to what is expected without utilising real-life Time-of-Use (ToU) data, house specifications or any other available real-life data. The generated abstract demand is best viewed as a practical example of the real demand in the targeted area.

The abstract residential demand is generated from the mutual interaction between the 'abstract' people and their 'abstract' appliances, under the influence of their usage patterns and appliance distributions within the home. 'Abstract people', which follows a generalised human description, is used to model people and their interactions, while 'abstract appliances' means that the demand generator utilizes appliance demand 'envelopes' that host the range of possible variations of appliance demand. This is adequate since the proposed solution is based on the assignment management of HVAC appliances for dwellings regardless of house specification, number of rooms, type of insulation, or pattern of appliance use. The application of the model in the development of the strategy has been proven for the purposes of this research.

6.3.4 Foundations of the Abstract Residential Demand Generator (ARDG)

The foundations of the abstract residential demand are:

1. **Dwellings and rooms:** environments where the interaction of inhabitants and appliances occurs on a daily basis, influenced by the size and room composition; the size of the dwelling is a direct reflection of the financial capability. The demand is generated for different houses ranging from a minimum size low-income family house having 1 bathroom, 1 kitchen, 1 living room, and 1 bedroom to a wealthy family house having multi-baths, 1-2 kitchens, 1-2 living rooms, 1-2 guest rooms, and multi-bedrooms.
2. **Families' sizes and financial levels:** the interaction between the size of the family and the size of their house defines the pattern of appliance usage and shape of demand, e.g. large families living in small houses have a different demand shape from small families living in large houses**.**
3. **Family members and occupation:** families comprise one or more people,

their number, occupation, and behaviour throughout determine their demand curve. People are classified according to their gender, age, and occupation. In the current version of the demand generator there are ten types of people listed in Table 6.1 and it is possible to add any number of members. The two types of 'men' differ only in their occupation, each following a different daily time schedule; the same is established for 'women'. There are however three types of 'teenagers', and although all are students, they follow different interests and hobbies reflected in their daily schedule. In addition, there is one type of 'elderly people' due to the similarities in their daily activities; the same is true for 'children' and 'babies'. Other types of people such as unemployed men and women can be added if a need is identified**.**

Table 6.1: Modelled people classification.

	Person	**Gender**	**Age range**	**Occupation**
1	Man	Male	19-60	Employed
2	Man	Male	19-60	Self-employed
3	Woman	Female	19-60	Employed
4	Woman	Female	19-60	House wife
5	Elderly	Both	>60	Unemployed
6	Teenager	Both	13-18	Student, general
7	Teenager	Both	13-18	Student, PC
8	Teenager	Both	13-18	Student, Out
9	Child	Both	6-12	Student
10	Baby	Both	< 6	Baby

4. **Activity profiles and daily tasks:** human activities are based on a need to perform a certain action owing to an internal or external motive; to satisfy this need one or more events must be initiated which could involve one or more appliances. A human general activity state diagram representing the 'causal model' [234] shows that each activity is started by a need, may or may not include one or more sub-activities and ends by one or more events on a household object (here appliances); Figure 6.9 shows this chain.

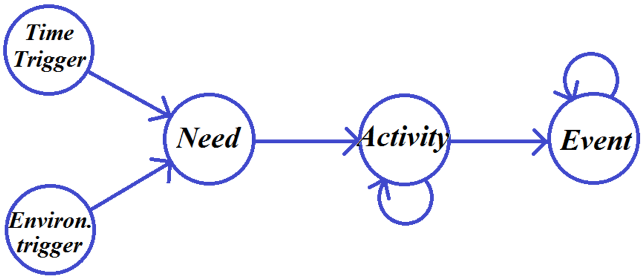


Figure 6.9: Activity-event chain flow [234].

Activities have many attributes that define how they are characterised. Figure 6.10 shows seven different activities attributes which are; the activity occurrence probability, its time of occurrence, duration, alternative activity if this one doesn't occur, mutual occurrence which specifies if this activity is shared with another person, its season, and appliances involved in its execution. Activities can be broken down further into sub-activities, like cooking, which involves washing food for example, and the resulting events from this activity could trigger one or more events, such as washing clothes which triggers the use of the clothes washer, tumble dryer, and finally the iron.

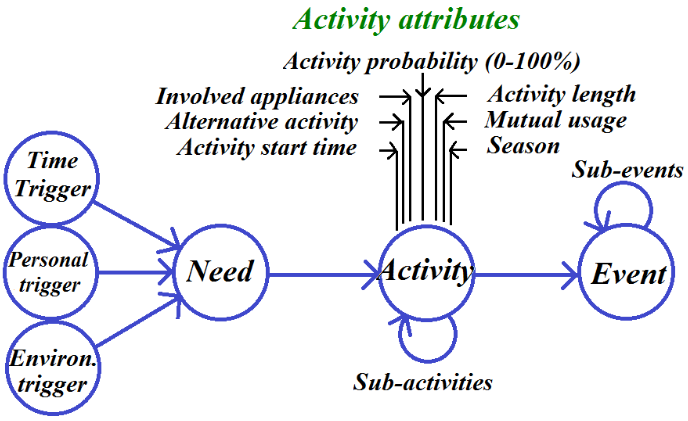


Figure 6.10: Activity attributes.

In general, each activity has a certain probability of occurrence and one or more alternative activities that could replace it if it is not executed or performed e.g. a person who typically goes for exercise in the afternoon does not do so every day, as on some days he may just rest at home. Figure 6.11 shows these inter-activity relationships and probabilities.

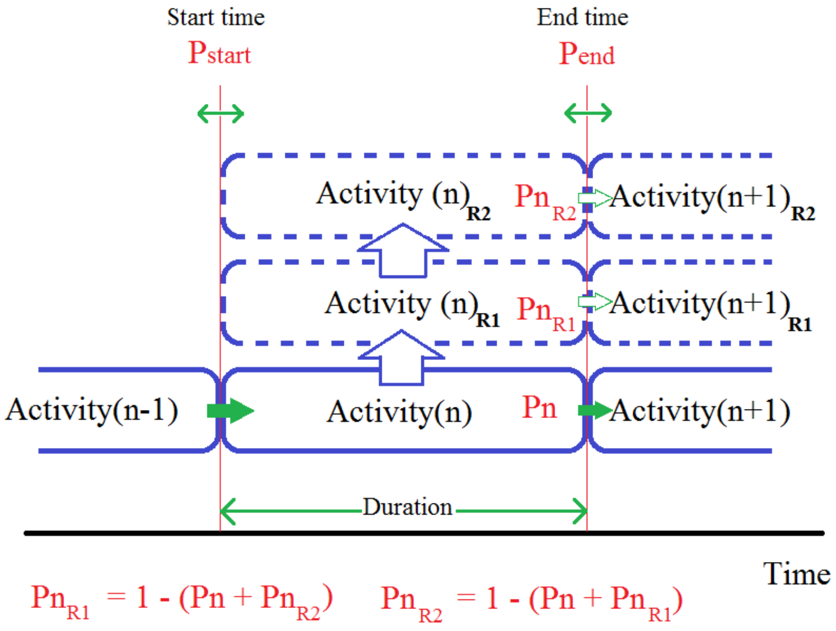


Figure 6.11: Activity sequencing.

The activity probability of occurrence (P_n), starts as (P_{start}), and ends as (P_{end}); each activity has a start and end time probability and both of them specify the duration of that activity. In addition, its occurrence probability determines whether it or one of its alternatives will occur. This inter-dependency and multi-path relationship between activities is best viewed as an activity tree which hosts all activities and sets all master and alternative paths (Figure 6.12). Some activities can be repeated for (n) times, like a player who decides to extend the game.

5. **Finite-State Machines (FSM):** FSMs are a well-known electronic design technique and at the same time have applications in software development **[235]**. A FSM can be described as a design/modelling technique in which system or process behaviour is described as a sequence of finite consecutive states in which that system or process resides in one of them at any moment. The output of each state and its transition-related parameters to the next state are defined. The benefits of using such an approach is that the FSM model offers a systematic and clear approach to describing the behaviour of a system or process resulting in an optimum or near optimum

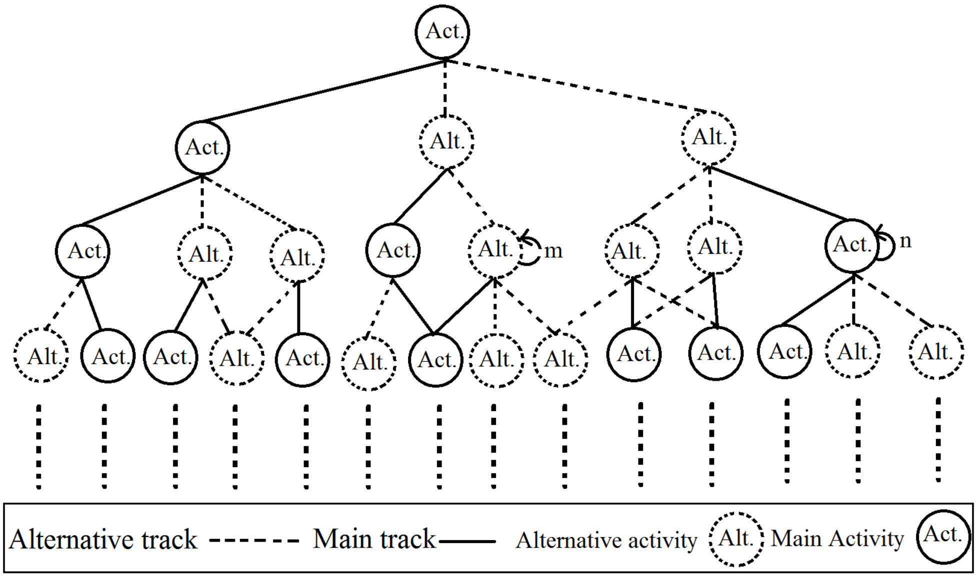


Figure 6.12: Activity tree.

modelling of it. In addition, the method does not require prior knowledge of the specifics of the modelled system or process [236] and it is highly effective in scarce data scenarios. On the other hand, it is not practical to use FSMs if the number of states is too high, e.g. more than 100, or too low, e.g. 2-3 due to the complexity of the first and the simplicity of the second. FSM consists mainly of a set of finite states, inputs, transitions, and actions to be performed when the transition is to the next state [235]. FSMs can be represented by state diagrams and state transition tables.

Furthermore, people are known to be creatures of habit and many essential daily activities are repeated nearly every day e.g. sleeping. Further, although people have many things in common when it comes to daily routine, it is nevertheless important to accentuate their respective differences. Each individual defined in the demand generator follows unique timings and activities that distinguish him from others.

FSM is used to represent the daily activity profile for each 'abstract' person, manifest as unique FSM state diagrams shown in Figure 6.13 to Figure 6.18 for different family members. In these state diagrams, the first activity is sleeping which is located at the far left always and it starts at mid night for all categories. In the same way, all activities end with sleeping, so this state diagram covers the period from (00:00 – 23:59). There are no limitations to the sequence, type, or duration of subsequent operations as long as their temporal boundaries are set correctly. The resulting daily schedule will be more accurate and detailed if careful investigation of the daily activities of the targeted people is recognised and recorded as in the TOU surveys which, unfortunately, are not routinely available in many cases.

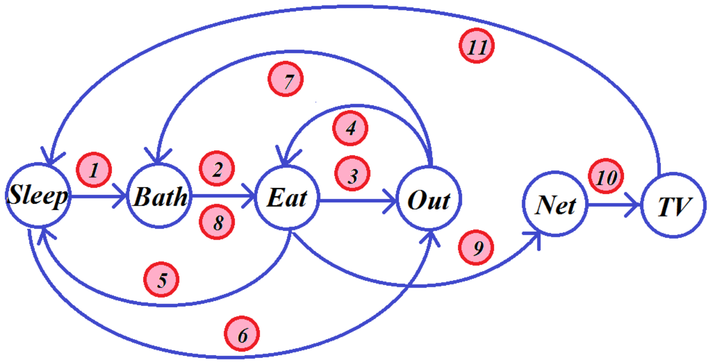


Figure 6.13: A state diagram of a typical daily routine of an employed man.

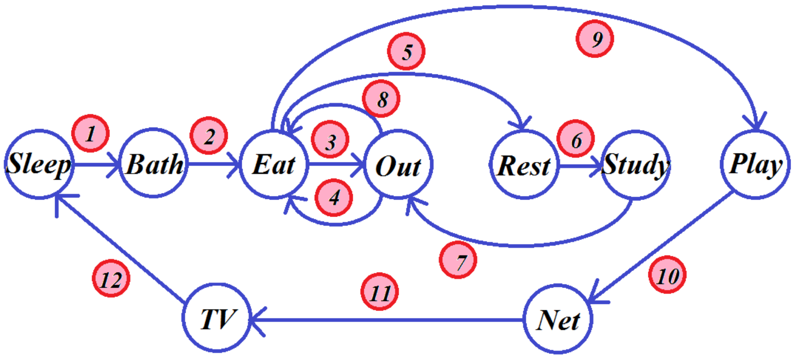


Figure 6.14: A state diagram of a typical daily routine of a child.

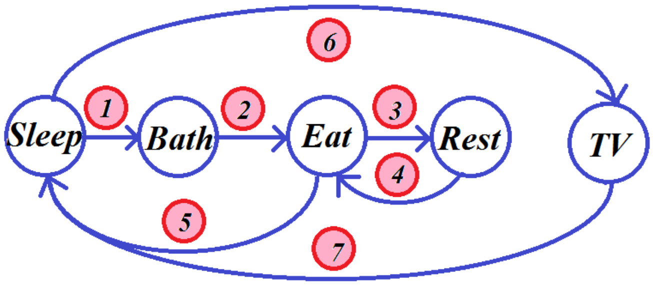


Figure 6.15: A state diagram of a typical daily routine of an elderly person.

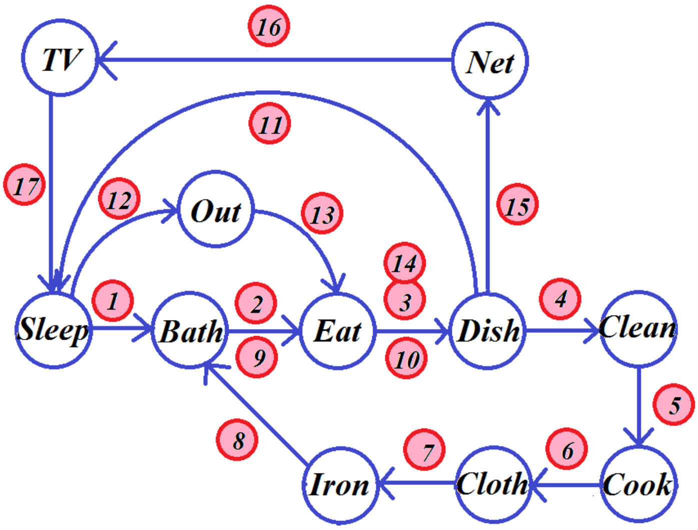


Figure 6.16: A state diagram of a typical daily routine of a house wife.

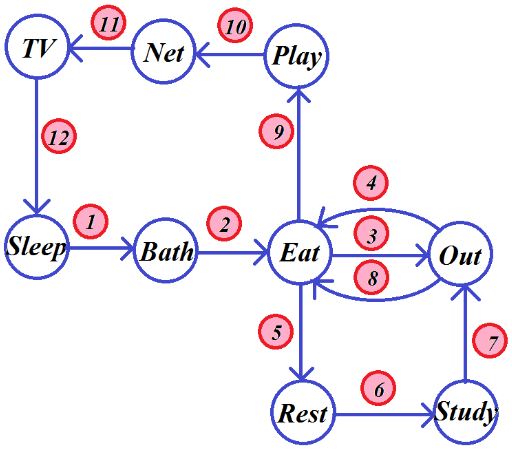


Figure 6.17: A state diagram of a typical daily routine of a teenager.

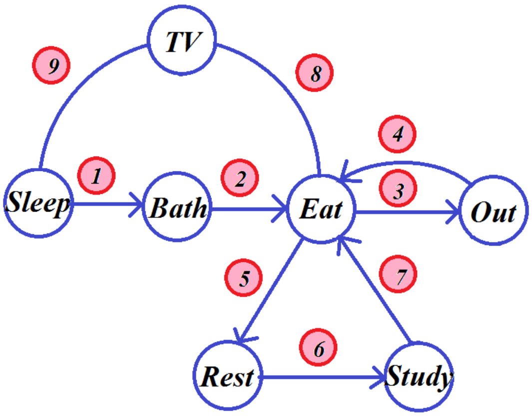


Figure 6.18: A state diagram of a typical daily routine of a baby.

The profiles of family members are translated into matrices, their columns are minutes of the day, while the rows are the appliances they interact with. Each cell in the matrix represents the amount of power that individual has consumed at that minute during the day. The matrices are projected over a final demand matrix of the same structure and its columns representing the total residential demand.

Figure 6.19 illustrates the total demand generation process.

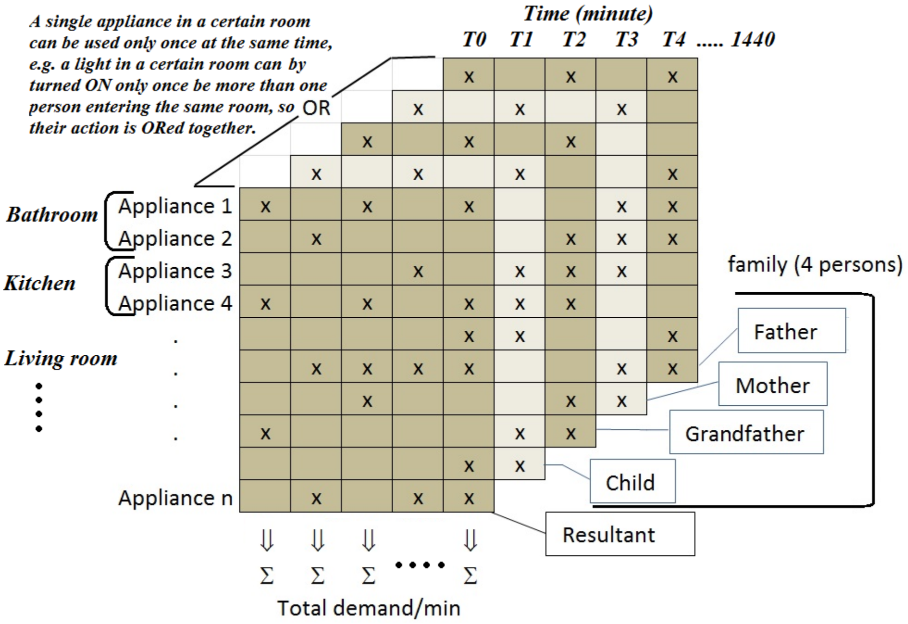


Figure 6.19: Demand generation principles.

6. **Financial capability:** the financial status is most readily reflected in the number of appliances within the home, the appliance demand and house size. In the abstract demand generator rich families are characterised by their tendency to buy more and higher demand appliances.
7. **Active and passive occupancy:** 'active occupancy' is defined as the activities of dwellers whilst at home generating demand, the opposite of 'passive occupancy' in which dwellers at home are inactive as in the case of being asleep; as an example, Figure 6.20 shows the active occupancy of 50 UK houses with three main activity periods: low, medium, and high. The first is during sleeping hours, the second during work/study hours and the third is at rest period during the evening time. The ARDG creates the active

occupancy through aggregating the demand of the appliances they use during daily activities.

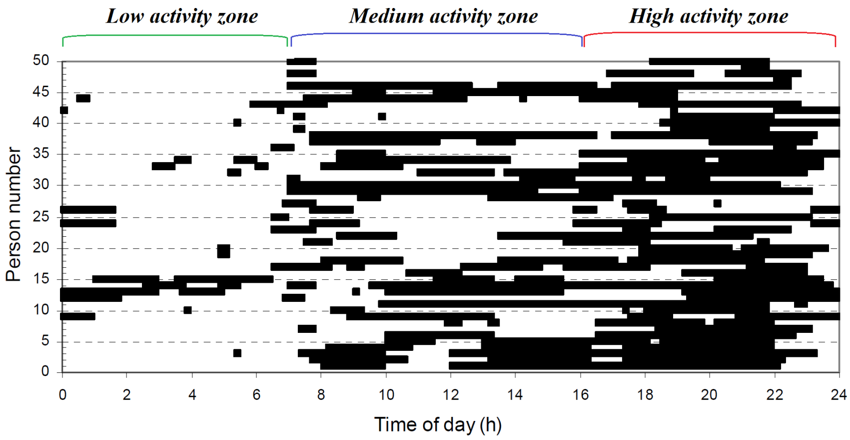


Figure 6.20: Active occupancy in 50 UK houses [237]

17 different daily activities in the demand are shown in Table 6.2 related to typical daily operations and activities performed by people. In general, each activity consists of three parts (some has two and some has only one); the middle part is the main activity preceded by a starting part and ends by an ending one. These activities are categorised into three groups: standalone, dual-part, and tri-part activities; and each one has a specific probability and duration depending on the individual. New activities can be added, and established ones can be expanded to produce a more accurate demand, Table 6.2 summarizes these activities. Note that the centre of the table represents the main activities which have a probability of (1).

8. **Appliances and their usage:** different models, manufacturers, operating modes, uses, service fields, and capacities have a direct impact on power demand, in addition to that individual's consumption and occupation patterns that shape this power demand. The appliances map shown in Table 6.3 is based on the field survey. Iraqi households rely mainly on natural gas-based cooking and heating appliances due to cost, availability, and the construction material (reinforced cement) of houses which prevents and in worst case limits, the fires caused by gas accidents. Electric cookers are used as backup in the case of the disconnection of the gas supply.

Table 6.2: Daily activities details

Task Name	starting Activity	Duration (min)	Probability	Main Activity	Duration (min)	Ending Activity	Duration (min)	Probability	Room
Bath	none	-	-	Bath	Depends on the person	none	-	-	BA
Cook	wash food	2	0.1	Cook		none	-	-	KI
Clean	none	-	-	clean house		wash hand	2	1	All
Eat	wash hand	2	1	Eat		wash hand	2	1	LR
Play	none	-	-	Play		none	-	-	GR
Internet	none	-	-	Internet		none	-	-	BR
Iron	none	-	-	Iron		none	-	-	BR
Go out	Wear clothes	15	1	Go out		Take off clothes	5	1	BR
Go to work	Wear clothes	15	1	Go to work		Take off clothes	5	1	BR
Go to school	Wear clothes	15	1	Go to school		Take off clothes	5	1	BR
Make Juice	none	-	-	Make Juice		none	-	-	KI
Rest	none	-	-	Rest		none	-	-	LR
Sleep	none	-	-	Sleep		none	-	-	BR
Study	none	-	-	Study		none	-	-	BR
Watch TV	none	-	-	Watch TV		none	-	-	LR
Wash dishes	none	-	-	Wash dishes		none	-	-	KI
Wash clothes	None	-	-	Wash clothes		none	-	-	KI

BA: Bathroom, KI: Kitchen, LR: Living Room, BR: Bedroom, GR: Guest Room, All: All Rooms

Table 6.3: Appliance population details.

	Appliance	Code	Min (W)	Max (W)	Avr. (W)	Control type	Basic set	HVAC	Power eager	Notes
1	Lights	LI	20	100	60	Slider*	x	-	-	CFL
2	Ceiling fan	CF	50	100	75	Slider	x	x	-	
3	Deep Freezer	DF	100	800	450	Slider	x**	-	-	
4	Refrigerator	RF	100	730	415	Slider	x	-	-	
5	Washing machine	WM	350	930	640	ON/OFF	-	-	-	Without heating
6	TV	TV	200	350	185	ON/OFF	x	-	-	
7	DVD/Receiver	DVD	20	30	25	ON/OFF	x	-	-	Operate always with TV
8	PC + monitor	PC	200	400	300	ON/OFF	-	-	-	
9	Game console	GA	100	100	100	ON/OFF	-	-	-	Need TV to operate
10	Laptop	LT	50	80	65	ON/OFF	x	-	-	
11	Stereo	ST	70	400	235	ON/OFF	-	-	-	
12	Blinder	BL	100	800	450	ON/OFF	-	-	-	Kitchen set
13	Air conditioner	AC	1500	3500	2500	Slider	-	x	-	Typical AC demand 3500 W
14	Air cooler	CO	300	1000	650	Slider	-	x	-	≥ 2200 ft^3/min
15	Mist fan	MF	80	300	190	Slider	-	x	-	
16	Water heater	WH	2000	3000	2500	Slider	-	-	x	
17	Space heater	SH	1000	2000	1500	Slider	-	x	-	
18	Iron	IR	1000	2200	1600	Slider	-	-	x	
19	Hair dryer	HD	900	1500	1200	Slider	-	-	x	
20	Water pump	WP	250	380	315	ON/OFF	-	-	-	Found in every house

* In HVAC appliances ‘Slider’ control is a typical ‘thermostat’, in lights it is a dimmer, and in fans and heaters it is a multi-position switch.

** depends on the family.

For the sake of fulfilling the requirements of the proposed system, appliances are grouped into three categories: the basic set that must be powered to provide minimum household services, at least one HVAC appliance used to cool the dwelling, and high-power consuming appliances operated with utility power only. The rated power of the range of appliances differs between model, size, and manufacturer; in the ARDG appliance, power is set between a known minimum and maximum according to what is offered in the local market. Finally, the type of control is set for each appliance i.e. ON/OFF or slider, the latter representing thermostats and dimmers. Some appliances such as water pumps are typical in Iraqi houses due to weak water flow rate.

9. **Appliance demand profiles and envelopes:** the different needs of families, their behaviour, and financial ability have motivated manufacturers to produce a mix of appliances that differ in many respects; these differences are manifest as spikes and irregular power demand profiles. In the ARDG model an appliance demand envelope is used to smooth fluctuations and behavioural spikes. This treatment is beneficial in some cases, such as clothes washers and not in other cases, such as an oven, where the demand is more regular by nature. Figure 6.21 shows three different microwave oven cycles within their envelope.

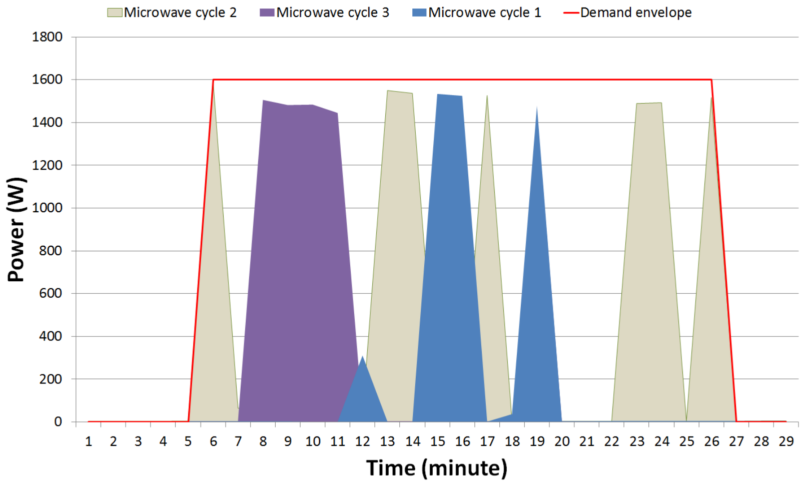


Figure 6.21: Microwave cycles and their envelope [238].

10. **Vicinity sharing and simultaneous appliance usage:** the size and make-up of dwellings have a direct effect on appliance usage patterns[66], usage times[67], and eventually overall demand. Appliance demand is also influenced by their distribution inside the house[68]. The environment results in 'vicinity sharing' i.e. members of the same family share the some appliances due to their limited number and/or ready availability, e.g. watching TV. The ARDG framework takes into consideration the effect of simultaneous appliance usage when generating the required demand. Table 6.4 shows a typical distribution of appliances inside a house. A typical house has one living room, one guest room, and one kitchen, more than one bathroom and one or more bedrooms. Large houses tend to have more than one guest room.
11. **Time granularity**: time granularity is an important factor in generating demand profiles. A very high time sampling rate can generate superfluous data, while lower rates such as 30 mins and 60 mins mask important features. In the ARDG, the time granularity is set to 1 min, thus a day is divided into 1440 time slots, providing a description of the demand of each appliance over a full day.
12. **Seasonal effect**: variations in seasons create tangible changes in temperature and in some geographies in humidity as well. The environment has the ability to investigate the impact of seasonal changes on residential demand. Table 6.5 illustrates the usage of air conditioning/heating across the seasons, with little or no difference between spring and autumn

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[66] e.g. Number of bathrooms and the availability of master bathrooms draw the pattern of their usage.

[67] Large families living in small houses use some appliances, such as a guest room AC, more often than small ones due to larger number of possible family friends, less space for doing some chores such as study or doing some hobbies.

[68] A stereo in someone's bedroom is most likely to be used by that person alone compared to another one in a common place such as a living room.

Table 6.4: Distribution of appliances in different rooms in a typical house.

	Room	Appliance	Code	Typical number of this type of room
1	Bathroom	Lights	LI	≥1
2		Space heater[69]	SH	
3		Water heater	WH	
4	Kitchen	Lights	LI	1
5		Fan [70]	CF	
6		Deep freezer	DF	
7		Refrigerator	RF	
8		Water pump[71]	WP	
9		Stereo	ST	
10		Blinder	BL	
11		Washing machine[72]	WM	
12	Living room	Lights	LI	1
13		Fan	CF	
14		Air conditioner	AC	
15		Air cooler	CO	
16		Mist fan	MF	
17		Space heater	SH	
18		TV	TV	
19		DVD/Sat. Receiver	DVD	
20		PC + monitor	PC	
21	Guest room	Lights	LI	1
22		Fan	CF	
23		Air conditioner	AC	
24		Space heater	SH	
25		Game console	GA	
26	Bedroom	Lights	LI	≥1
27		Fan	CF	
28		Air conditioner	AC	
29		Space heater	SH	
30		Iron	IR	
31		Hair dryer	HD	
32		Laptop	LT	
33		Stereo	ST	

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[69] Bath room space heaters are typically much smaller than other space heaters.

[70] Houses normally have table fans as well but they are included with ceiling ones here.

[71] Water pumps are used widely in Iraq due to the low flow rate of water supply

[72] Some families put their washing machines in other places such as bathrooms since laundry rooms are not typical in the Iraqi house design.

Table 6.5: Seasonal impact on HVAC usage.

	Season	Fans	Air conditioning	Space heating	Water heating
1	Spring	x	-	-	-
2	Autumn	x	-	-	-
3	Winter	-	-	x	x
4	Summer	x	x	-	-

6.3.5 Demand Generation by Multi-Plane Projection

The ARDG generates residential demand through the aggregation of the individual activities of individuals living in the residential area, following the principles of [239] who stated that "The electricity demand of households can be optimally modelled as a result of the activities performed by their occupants. Residential use of electrical appliances is determined by residential activities, which are themselves determined by residential occupancy".

Figure 6.22 shows the various stages used in the demand generation process showing three types of planes representing different types of information and relationships:

- one 3D - category, occupation, time
- four 2D - seasons (sub-activity-appliances)
- three 2D - financial levels (appliance-power)

Following this principle, the residential demand is initiated by selecting a family member as in [240]; the category of the individual (1), occupation (2), using this information to obtain a daily schedule (3) and dis-aggregating the schedule into various activities (4) as in [234]. Each activity in the daily schedule is governed by an occurrence probability, start time, duration, participating appliances, according to seasonal constraints, and an alternative activity. The time period during which the activity is executed is then set (5) and time slots of this activity (in single minutes) are established (6). The relevant season is then set (7) and the appliances needed to complete the selected activity are chosen (8). In the following step (9) the financial status (10) of the family is set which determines the mix of appliances used to calculate the household demand. In step (11) the participating appliances are matched with their demand (12) and aggregated (13) to produce the total demand at that time slot (minute). This operation is repeated for 1440 (24 * 60) times to generate residential demand for an entire day.

6.3.6 The Assumptions

Certain assumptions have been made in generating the residential demand profile:

1. each dwelling comprises a living room, bathroom, kitchen, guest room and bedrooms
2. every house has at least one kitchen and one bathroom, regardless of economic status
3. all similar rooms have similar appliances i.e. in a multi-bedroom house all bedrooms have the same furniture
4. all individuals described in a category follow the same daily activities but with different probabilities. New individual following new sets of activities can be created.
5. temperature and humidity can be measured every minute and their daily average can be calculated.
6. the rated power of all appliances lies between a predefined minimum and maximum; any value between these two limits can be assigned to the targeted appliance
7. bathroom space heaters are used in all houses during winter
8. water pumps are used in all houses
9. laptops are part of the appliances in bedrooms only, they can be used anywhere but can only be charged in bedrooms
10. irons are available on a one-per-bedroom basis
11. all appliances have ON/OFF switches and relevant ones have thermostatic control.
12. all individuals have daytime work periods only; no night shifts are considered
13. infants are not included

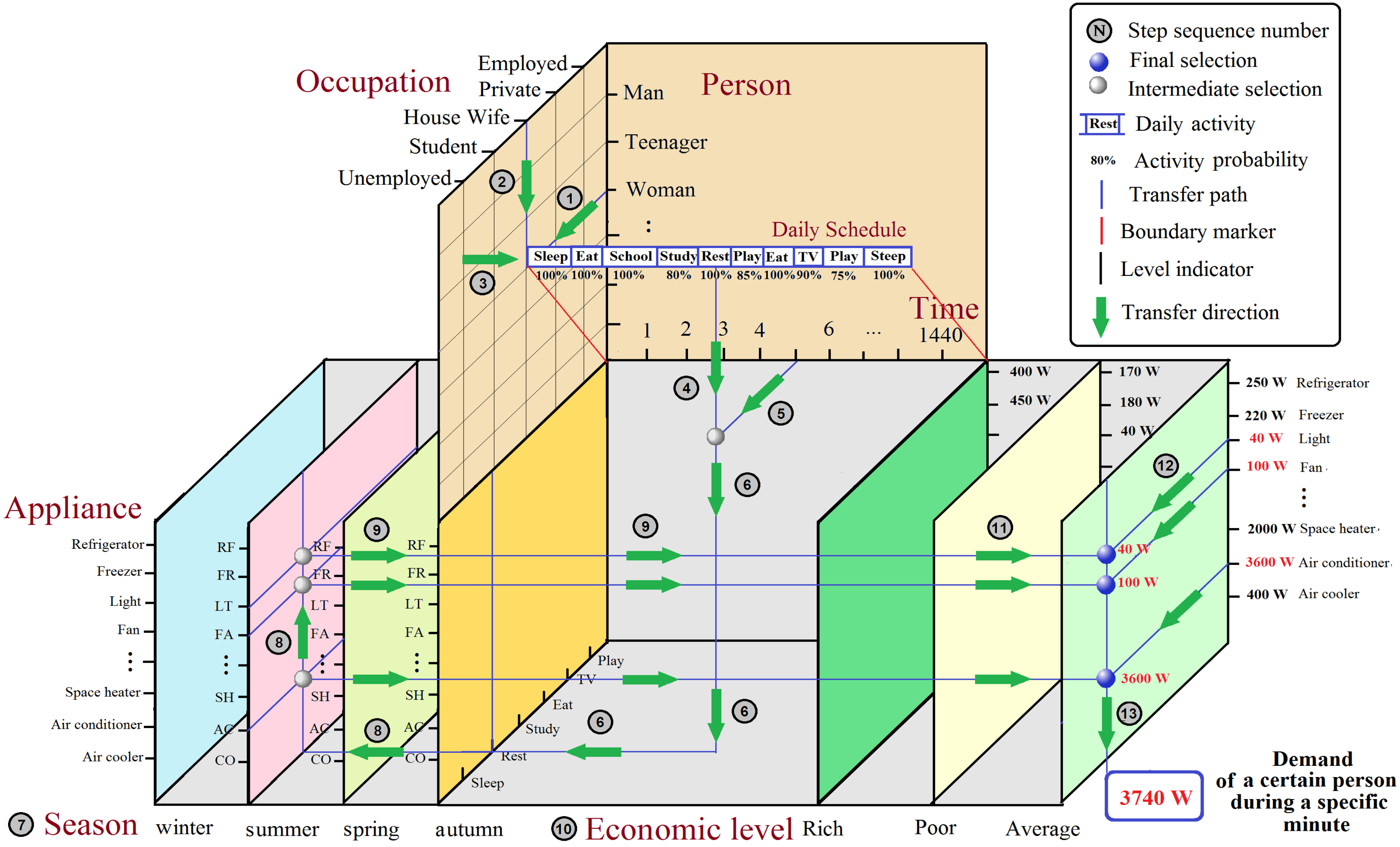


Figure 6.22: Multiple projection residential demand aggregation principles, sequences and their interaction.

14. pets are not considered
15. no appliance aging is considered
16. game consoles are assumed to be in the guest room
17. both tankless and storage water heaters are assumed to work as tankless ones.
18. one light in every room only and no consideration is given to stair and outer lights or light structures
19. since the ARDG in its current version is based heavily on the field survey, some appliances are not considered such as microwave ovens, electric cookers, electric kettles, toasters, coffee machines, dish washers, and tumble dryer machines because they are rarely used in Iraq, but they can be added when necessary.
20. blenders are a multi-function kitchen machine
21. ACs are assumed to be operational all the time, not practical if applied to normal operation especially at night but it is so when applied to a cyclic blackout scenario where there is no power for most of the day.

6.3.7 The Generated Demand Database

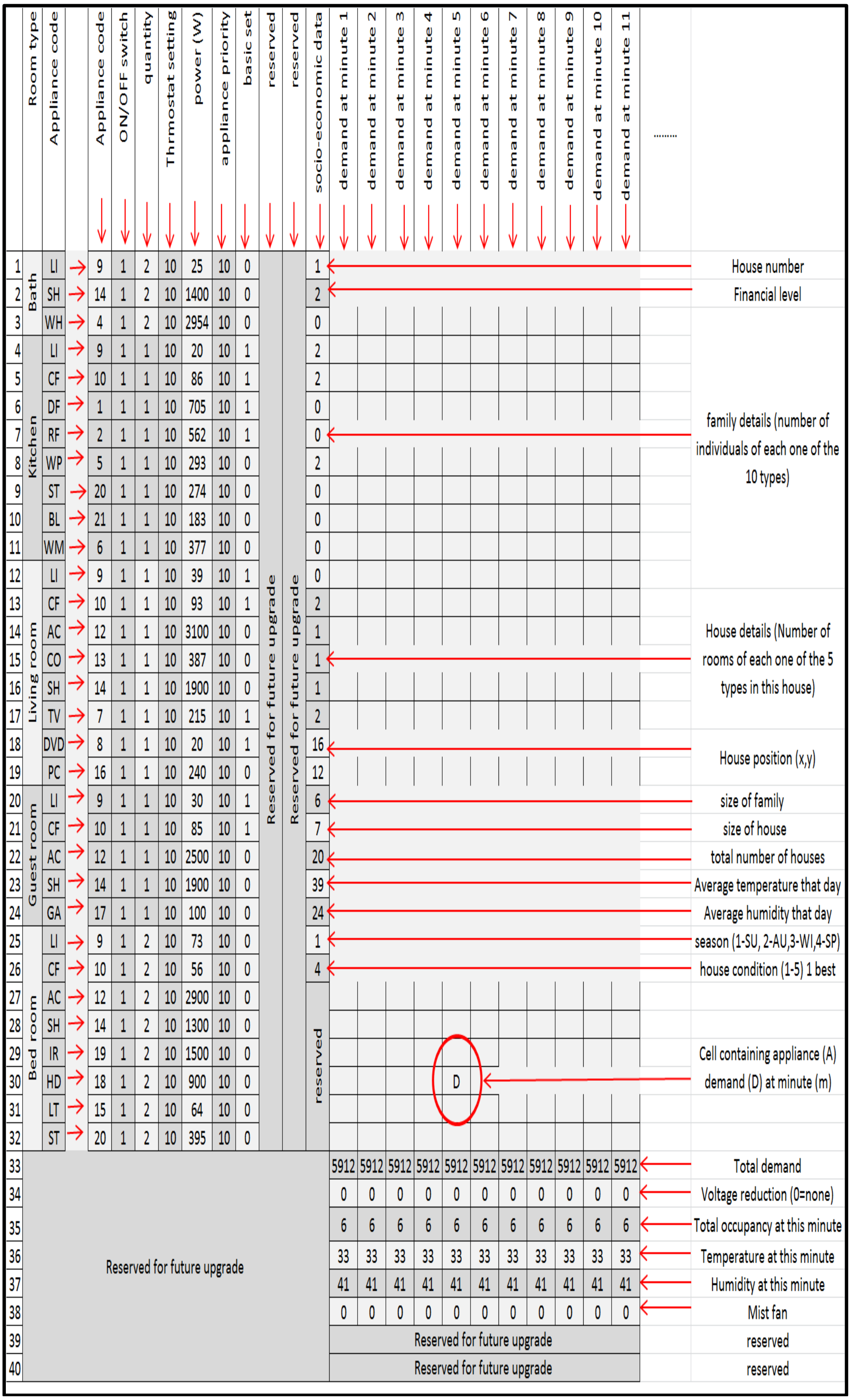
The ARDG has a dedicated database used to store its data which consists of a group of records on a one per house basis. Each record is designed as a multi-zone 2D structure having (58,000) data fields arranged in a 40 x 1450 data fields. A single record is divided into seven zones and each is used to store a certain type of data:

1. **House description zone:** in which the house structure and contents are stored e.g. number of rooms, house condition (1-5) where 1 represents a house in its best condition.
2. **Family description zone:** where the number of people of each category of the family is stored along with their financial status
3. **Appliance description zone:** holds detailed information about appliances i.e. identification code, number in that room, power, priority, and if it is a basic

set appliance or not

4. **Control zone:** holds the ON/OFF, thermostat settings, and percentage of voltage reduction which is applied to all appliances
5. **Environmental parameters zone:** holds the average and per minute temperature and humidity inside the house and the season.
6. **Detailed demand zone:** holds the demand of every appliance at a granularity of every minute during the day
7. **Occupancy zone:** holds the number of people inside the house at each minute throughout the day and night, providing information of both active and passive occupancy
8. **Reserved zone:** fields not used so far but kept for future use
9. **Miscellaneous information zone:** holds data used or intended to be used in the development stage of the residential demand profile, such as house address as an (X,Y) position in a location matrix (a 100x100 matrix used to position houses in a hypothetical area intended to be used for routing algorithm verification for exchanged data among different distributed local controllers).

The record structure of the database is shown in Figure 6.23, where the above zones can be identified. The database is supported by other smaller data structures used for developing various family and appliance description data.



	Room type	Appliance code		Appliance code	ON/OFF switch	quantity	Thrmostat setting	power (W)	appliance priority	basic set	reserved	reserved	socio-economic data	demand at minute 1	demand at minute 2	demand at minute 3	demand at minute 4	demand at minute 5	demand at minute 6	demand at minute 7	demand at minute 8	demand at minute 9	demand at minute 10	demand at minute 11	....	
1	Bath	LI	→	9	1	2	10	25	10	0	Reserved for future upgrade	Reserved for future upgrade	1													House number
2		SH	→	14	1	2	10	1400	10	0			2													Financial level
3		WH	→	4	1	2	10	2954	10	0			0													
4	Kitchen	LI	→	9	1	1	10	20	10	1			2													
5		CF	→	10	1	1	10	86	10	1			2													
6		DF	→	1	1	1	10	705	10	1			0													family details (number of individuals of each one of the 10 types)
7		RF	→	2	1	1	10	562	10	1			0													
8		WP	→	5	1	1	10	293	10	0			2													
9		ST	→	20	1	1	10	274	10	0			0													
10		BL	→	21	1	1	10	183	10	0			0													
11		WM	→	6	1	1	10	377	10	0			0													
12	Living room	LI	→	9	1	1	10	39	10	1			0													
13		CF	→	10	1	1	10	93	10	1			2													
14		AC	→	12	1	1	10	3100	10	0			1													House details (Number of rooms of each one of the 5 types in this house)
15		CO	→	13	1	1	10	387	10	0			1													
16		SH	→	14	1	1	10	1900	10	0			1													
17		TV	→	7	1	1	10	215	10	1			2													
18		DVD	→	8	1	1	10	20	10	1			16													House position (x,y)
19		PC	→	16	1	1	10	240	10	0			12													
20	Guest room	LI	→	9	1	1	10	30	10	1			6													size of family
21		CF	→	10	1	1	10	85	10	1			7													size of house
22		AC	→	12	1	1	10	2500	10	0			20													total number of houses
23		SH	→	14	1	1	10	1900	10	0			39													Average temperature that day
24		GA	→	17	1	1	10	100	10	0			24													Average humidity that day
25	Bed room	LI	→	9	1	2	10	73	10	0			1													season (1-SU, 2-AU,3-WI,4-SP)
26		CF	→	10	1	2	10	56	10	0			4													house condition (1-5) 1 best
27		AC	→	12	1	2	10	2900	10	0			reserved													
28		SH	→	14	1	2	10	1300	10	0																
29		IR	→	19	1	2	10	1500	10	0																Cell containing appliance (A) demand (D) at minute (m)
30		HD	→	18	1	2	10	900	10	0								D								
31		LT	→	15	1	2	10	64	10	0																
32		ST	→	20	1	2	10	395	10	0																
33	Reserved for future upgrade													5912	5912	5912	5912	5912	5912	5912	5912	5912	5912	5912		Total demand
34														0	0	0	0	0	0	0	0	0	0	0		Voltage reduction (0=none)
35														6	6	6	6	6	6	6	6	6	6	6		Total occupancy at this minute
36														33	33	33	33	33	33	33	33	33	33	33		Temperature at this minute
37														41	41	41	41	41	41	41	41	41	41	41		Humidity at this minute
38														0	0	0	0	0	0	0	0	0	0	0		Mist fan
39														Reserved for future upgrade												reserved
40														Reserved for future upgrade												reserved

Figure 6.23: The demand database showing a single record data structure.

6.3.8 The Generated Demand

In order to evaluate its performance, the DDSM-IDEA platform was used to perform a number of tasks. One elementary task was to produce the demand of a single house during the summer season; the overall demand shown in Figure 6.24 provides the total, HVAC, and basic set demand of a dwelling house during summer. The summer total demand in a hot country is dominated by the air conditioning demand; the demand shows that for 72% of the day air conditioning is used, contributing to more than 90% of the total demand, reaching 97% for 16.5% of the day. The main aim behind listing these figures is to emphasis the heavy footprint owing to air conditioning on the overall summer demand, fuelling the most severe cyclic blackouts.

Figure 6.25 shows the generated demand of 32 appliances distributed in a house comprising 2 bathrooms, 1 kitchen, 1 living room, 1 guest room, and 2 bed rooms during the summer season.

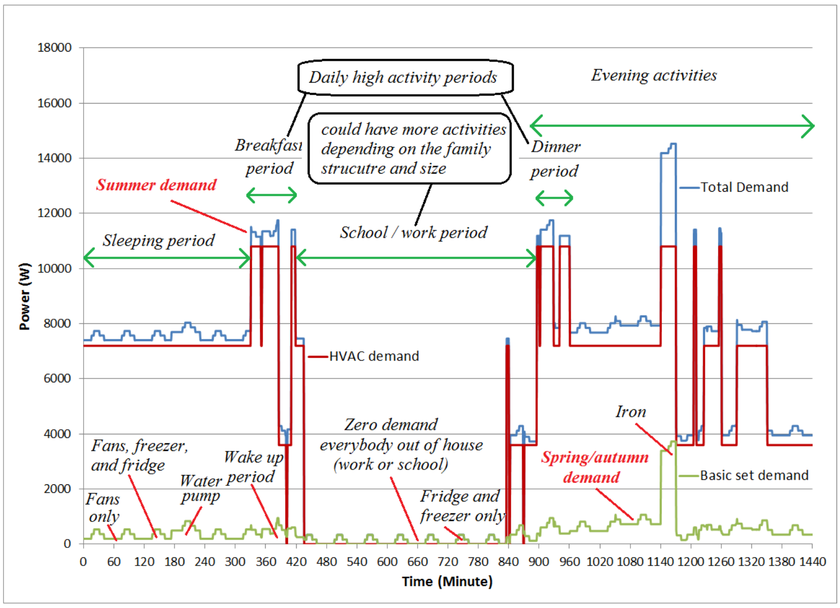


Figure 6.24: The total, HVAC and basic set abstract demand of single house during summer showing major activities during that day.

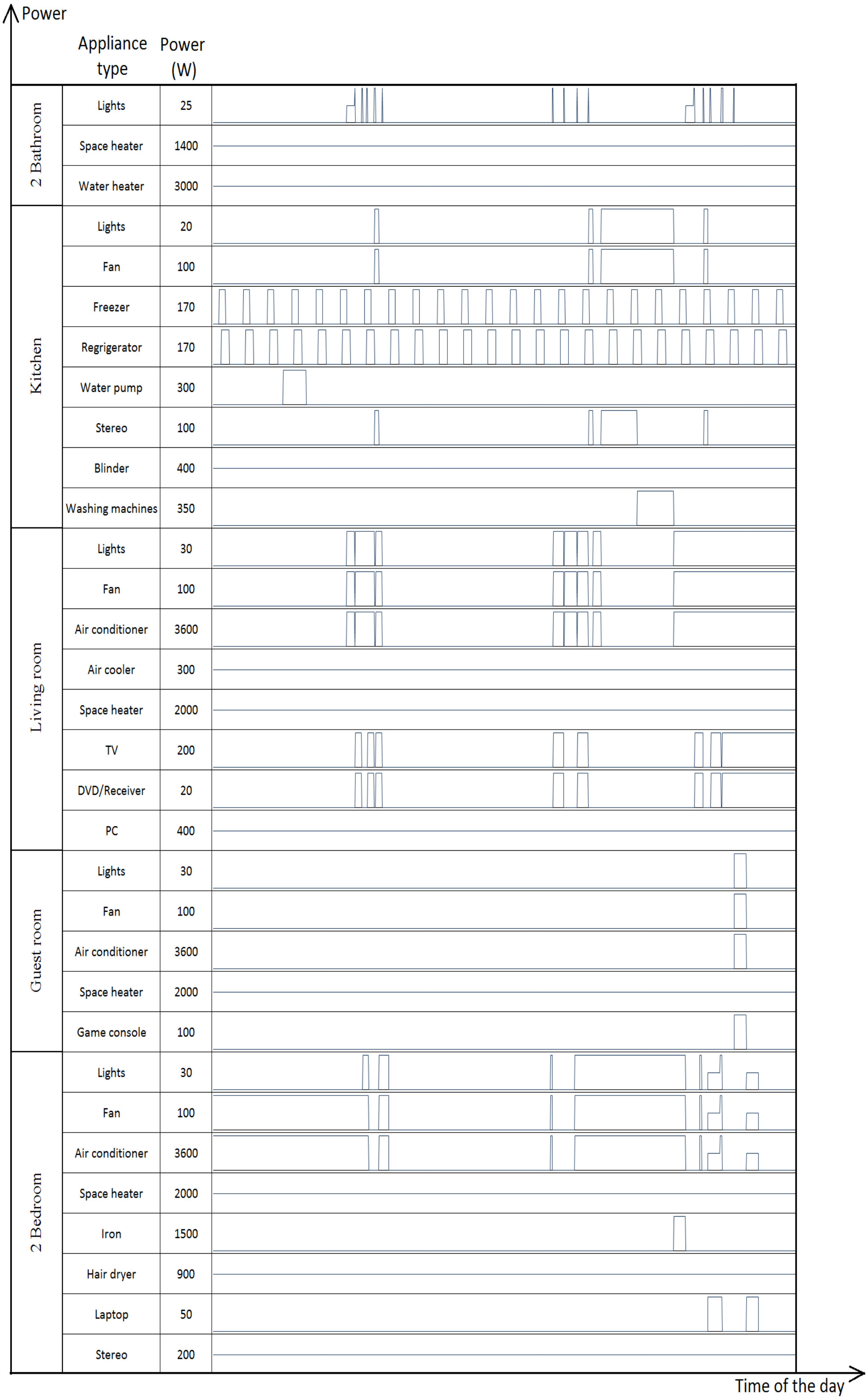


Figure 6.25: The generated summer abstract residential demand of 32 appliances.

The family consists of 2 self-employed men, 2 employed women, and 2 teenagers. The appliance usage pattern is typical, with some appliances not used such as bedroom stereo, PC, and blender, in addition to all heating appliances (since it is summer).

Figure 6.26 shows a vertically stacked graph showing the effect of financial status of a single family on generated residential demand during a summer day. The green area representing a poor family is small in contrast with the blue representative of a rich family. The evening period shows a low overall demand due to shared air conditioning as a consequence of gathering in the living room.

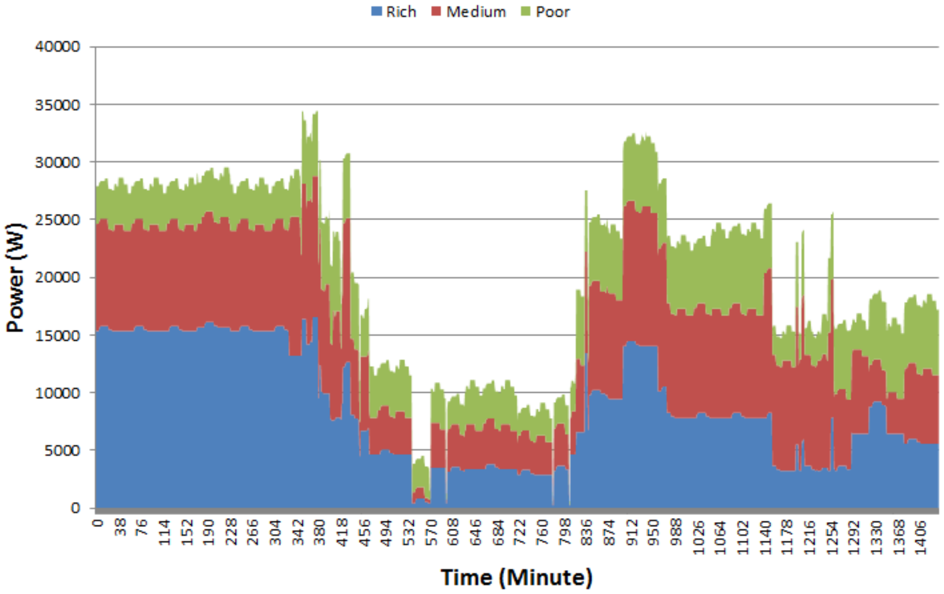


Figure 6.26: Vertically stacked graph showing the effect of finances on the generated demand of a single same family

6.4 DDSM-IDEA Evaluation

In order to assess the functionality of the DDSM-IDEA platform, two elementary DSM principles were implemented and evaluated.

Figure 6.27 shows a test result (not related to the targeted Kafaat residential area, PANDA system, or the developed strategy) of the DDSM-IDEA platform showing the effect of dimming the lights of 50 houses during spring to 50%, resulting in a reduction in the total demand by 8%. This result does not take into consideration any personal behaviours and changes in behaviours as a result of dimming the lights such as the extreme of operating more lights to compensate for the light reduction.

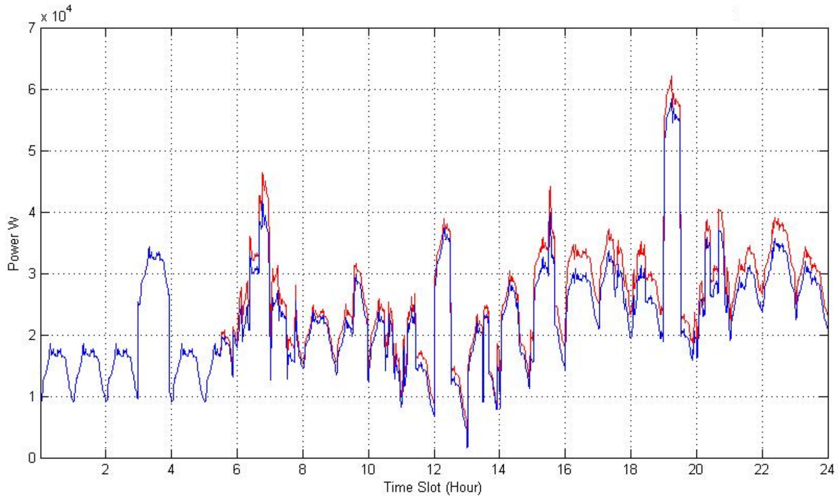


Figure 6.27: The effect of dimming the light to 50% of 50 houses during spring

Figure 6.28 shows a test result (not related to the targeted Kafaat residential area, PANDA system, or the developed strategy) of the DDSM-IDEA platform showing the effect of shifting the load of 20 tankless water heaters 20 minutes before and after the morning wake-up period in which all houses' occupants rush to their work places or schools; the result is a clipping of the demand peak at that time.

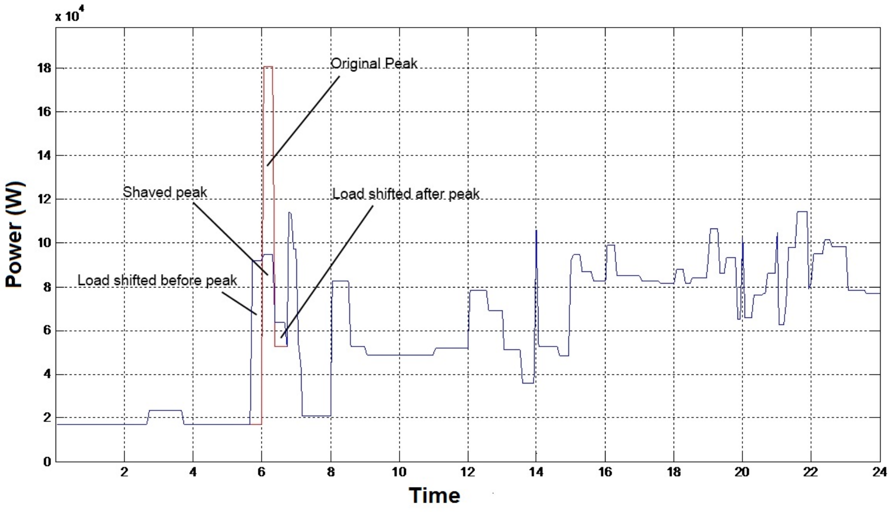


Figure 6.28: Clipping of peak demand of 20 tankless water heaters during morning.

6.5 Summary

This chapter describes the development of an IDEA referred to as the DDSM-IDEA, a platform developed to design and evaluate cyclic blackout strategies. The DDSM-IDEA has a variety of advanced features such as a built-in ARDG, agent support for traditional and distributed DSM strategy implementation, and test and demand analysis capabilities. The ARDG accommodates different family sizes, house sizes, categories of people, a plethora of appliances derived from the conducted field survey.

Demand envelopes are used in place of more granular demand shapes in order to accommodate relatively small variations in operation/rating between appliances from different manufacturers, modes of operation and sizes. The platform was used to produce the demand profile of certain houses as proof of functionality and to test/validate some elementary DSM strategies.

Chapter Seven
Cyclic Blackout Mitigation using Adaptive HVAC Interlocking

7.1 Introduction

The design and evaluation of the proposed cyclic blackout mitigation strategy based on adaptive interlocking of a different demand, different performance population of HVAC appliances is presented. The approach is compared to the widely-used load shedding. The results of adopting each type of HVAC usage right and the effect of their duration are presented and discussed. Detailed snapshots revealing the extent of interaction between agents is given to illustrate the technique. Lastly, the impact of the suggested strategy on the field of cyclic blackout mitigation is discussed.

7.2 Living under a Cyclic Blackout

Cyclic blackouts present a massive challenge in many countries, seriously impacting societies through hindering the growth of their economies. However it must not be forgotten that the main impact is on the individual, who invariably lacks the resources to install substantial standby generation and at the same time suffers the most since they have to manage the consequences daily. Routine activities under a cyclic blackout have to be prioritised or shifted/aligned to coincide with its occurrences. The situation is worsened in hot geographies where air conditioning is considered as the main element of an acceptable quality of life.

The residential demand consists of the aggregation of the demand of all appliances used in households. In a hot country like Iraq, oil-based heating and cooking appliances dominate but most households depend heavily on high power consumption air conditioning systems. This scenario yields an air-conditioning-dominated demand during the hot season. Figure 7.1 shows the demand of representative 20 households during summer. In order to reveal the impact of HVAC usage, the demand is segmented into three main components; air conditioning, basic set and ‘other’, adding up all yields the total demand.

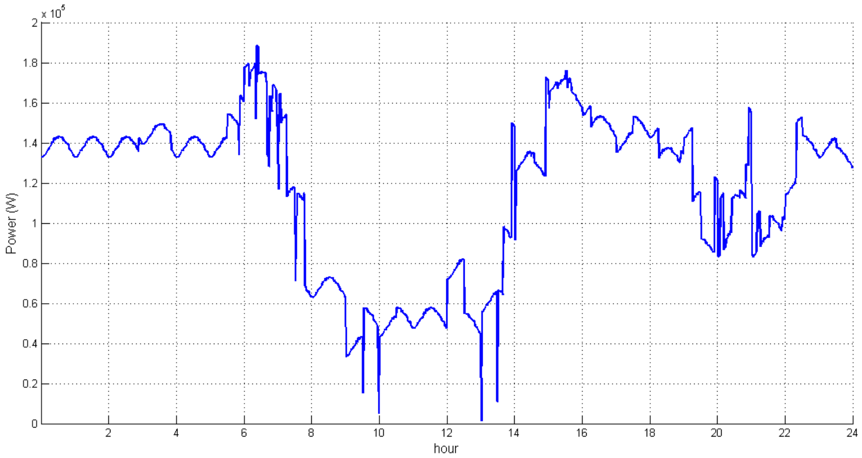


Figure 7.1: A typical daily demand example for 20 Iraqi families.

Figure 7.2 depicts the air conditioning and basic set components of the demand showing that the former dominates. These two components highlight the root of the challenge and inform the appropriate solution. The decrease in the overall demand during the period (1160-1350) is a consequence of a family gathering in the living room mainly for viewing the TV together.

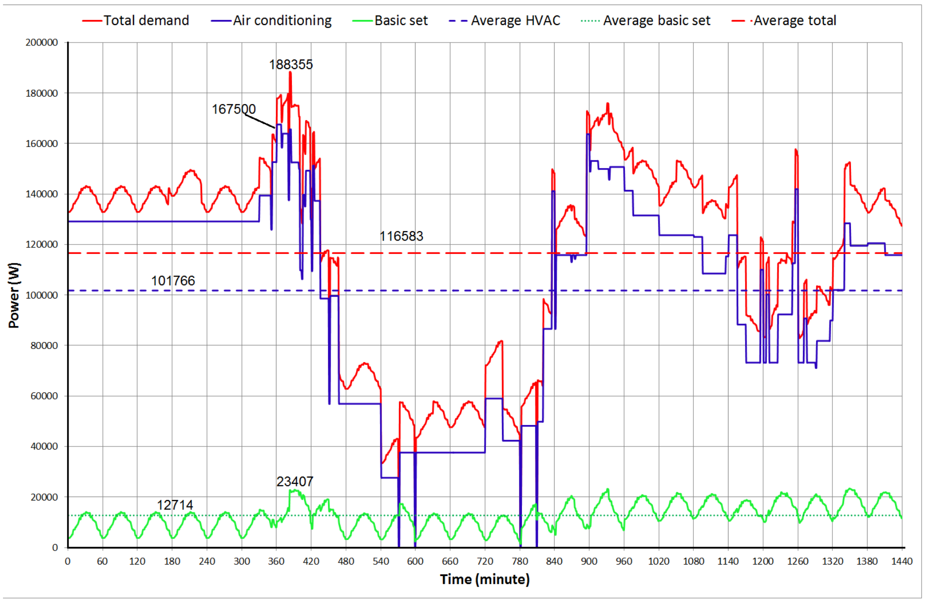


Figure 7.2: The total demand of 20 houses in summer, air conditioning and basic set demands.

Table 7.1 shows maximum needed power and average consumed energy for the main demand categories (HVAC and basic set) in addition to the overall total of the same 20 Iraqi houses whose demand was drawn in the previous figure. It is worth noting that there is no fixed definition of what constitutes the basic set, but its composition can be redefined to cover the needs of other environments or for different circumstances as in the case of severe power shortages where the basic set in that extreme can be reduced to just a single light depending on the power scarcity. These averages, maximums and totals provide an indicative estimate of the average and the maximum consumed power for a single household. Air conditioning contributes 87.3% of the overall energy average and its maximum consumed power during the day represents 89% of the overall maximum. The average basic set energy demand, according to the basic set definition, represents only 10.9% of overall average energy consumed while its maximum is 12.43% of the overall power maximum. The average air conditioning consumed energy is ~5 kWh per household while for the basic set it is ~ 0.636 kWh, 12.5% that of average air conditioning demand. The average share of each household in the basic set maximum power is 1.17 kW while for air conditioning is 8.375 kW.

Table 7.1: Summer demand components of 20 houses[73].

<table>
<tr><th colspan="2" rowspan="2">Parameter</th><th colspan="3">Type of demand</th></tr>
<tr><th>HVAC</th><th>Basic set</th><th>Total</th></tr>
<tr><td colspan="2">Maximum needed power (kW)</td><td>167.501</td><td>23.408</td><td>188.356</td></tr>
<tr><td colspan="2">Average consumed energy (kWh)</td><td>101.766</td><td>12.714</td><td>116.583</td></tr>
<tr><td colspan="2">Percentage of (maximum power/total)</td><td>89%</td><td>12.43%</td><td>100%</td></tr>
<tr><td colspan="2">Percentage of (average energy/total)</td><td>87.3%</td><td>10.9%</td><td>100%</td></tr>
<tr><td colspan="2">Maximum needed power / house (kW)</td><td>8.375</td><td>1.17</td><td>9.418</td></tr>
<tr><td colspan="2">Average consumed energy / house (kWh)</td><td>5.088</td><td>0.636</td><td>5.829</td></tr>
<tr><td colspan="2">Maximum consumed power/ person (kW)</td><td>1.232</td><td>0.172</td><td>1.385</td></tr>
<tr><td colspan="2">Average consumed energy / person (kWh)</td><td>0.748</td><td>0.093</td><td>0.857</td></tr>
<tr><td colspan="2">Population size: 136 person</td><td colspan="3">Average family size: 6.8 persons</td></tr>
<tr><td>Living rooms: 20</td><td>Guest rooms: 20</td><td>Bedrooms: 48</td><td colspan="2">total: 88 room</td></tr>
<tr><td colspan="2">Average person/bed room: 2.833</td><td colspan="3">Average person / living room = 6.8</td></tr>
</table>

---

[73] Totals and percentages don't add up since maximums are taken at different times during the day.

Figure 7.3 shows an example demand of 20 houses revealing the basic set demand components (lights, ceiling fans, TVs, satellite receivers, refrigerators, and deep freezers) generated as a result of the family's behaviour/interactions as defined through their personal profiles.

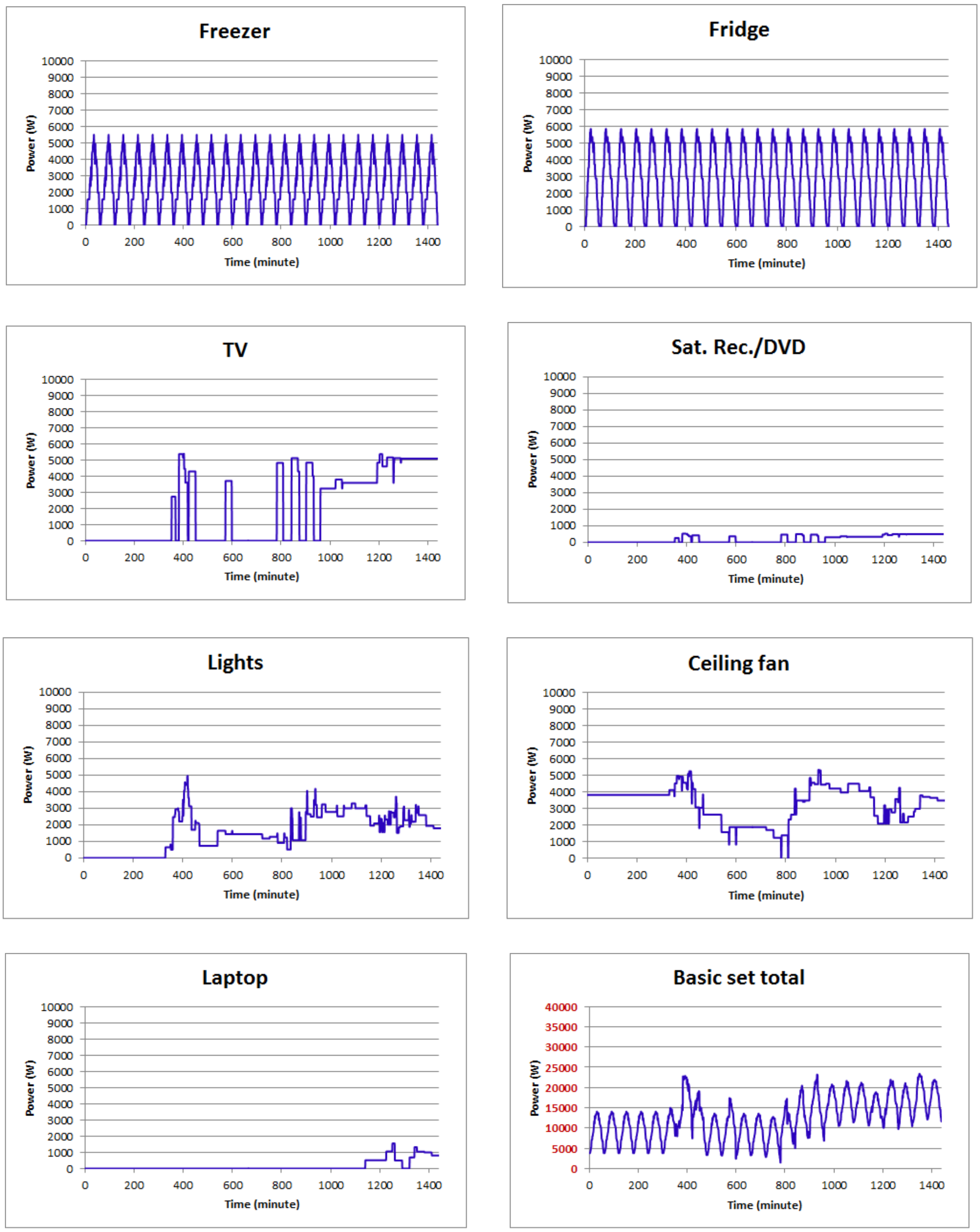


Figure 7.3: Basic set demand and its components for 20 houses during summer.

Some of these figures show a simplified version of the demand of some appliances e.g. fridge and freezer. These graphs are not related to the same overall demand shown in Figure 7.1.

After pinpointing the influential elements in the daily residential demand, its shape when subject to a typical (4 ON by 2 OFF) cyclic blackout is shown in Figure 7.4. The ON and OFF durations are not fixed and are assigned by the utility e.g. in critical situations the duty cycle could follow (1 ON by 11 OFF) schedule.

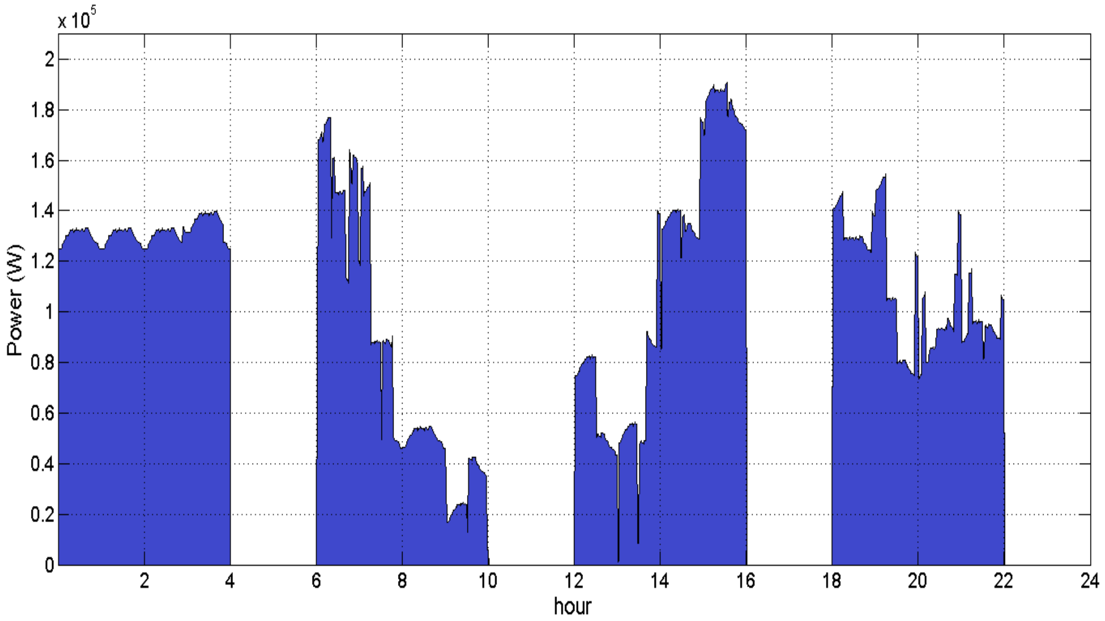


Figure 7.4: The total demand undergoing a 4 ON by 2 OFF cyclic blackout.

7.3 Cyclic Blackout Mitigation

The proposed cyclic blackout system starts the mitigation process by identifying the available power level, covering the basic set of appliances, and identifying and allocating the optimum combination of interlocked HVACs that can be powered by the remaining surplus power. It does that by interlocking three types of HVAC appliance for each household (AC, CO, and MF) and constructing an adaptive HVAC cluster e.g. for 20 houses there are 60 HVAC appliances in the cluster. The type of these operational 20 and their mix depends on the amount of surplus power. If there is sufficient power all ACs are activated, otherwise an optimum mix of ACs and COs are activated. If the power is even lower only COs are turned ON, otherwise a collection of COs and MFs are powered. If this is not possible, only MFs are powered. If the power level is less than that, then no HVAC is allowed to operate. Two principal strategies are invoked to allocate the HVAC power and their usage rights i.e. 'Fair share' and 'temperature-triggered' (Section 3.9). A 'usage right' here refers to *the right to operate an HVAC appliance* granted for a certain period of time.

Figure 7.5 shows the power profile after system activation, bridging the gap between each successive ON periods by covering the demand of a limited set of appliances from the surplus power from surrounding standby generation. The level of 'bridging power' differs significantly from the original demand and between OFF zones due to the variance in available standby power and in the amount of supported HVAC demand in each zone. ACs and COs are assumed to operate continuously when there is grid power while the payback effect on fridges, and freezers is not considered in order to make the comparison between the demand before and after PANDA's operation clearer. The effect of operating ACs and COs continuously during grid power ON periods and powering a subset when PANDA is enabled will result in an improved level of air conditioning throughout the day for all houses.

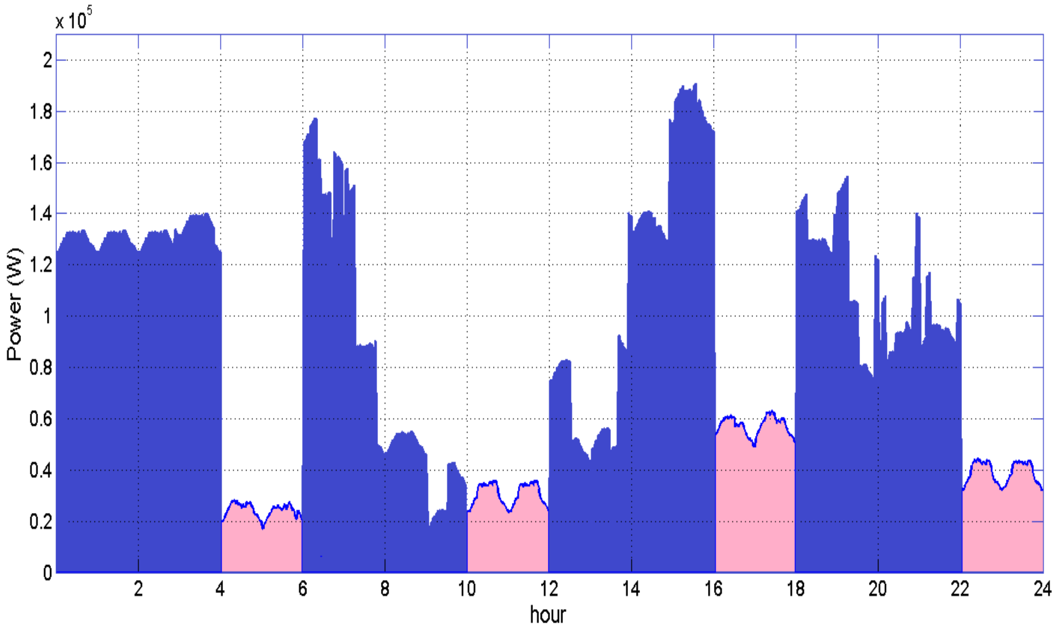


Figure 7.5: The result of applying the proposed system to a cyclic blackout.

Sufficient power is provisioned during an OFF cycle to cover a basic set of appliances and a single HVAC. The comparison between the cyclic blackout profile and post system activation shows that by managing the demand through monitoring and control it is possible to provide an acceptable quality of living during power down periods using just a fraction of the needed power during normal daily operation.

7.3.1 Fair Share Distribution

Under 'far share' usage rights, the proposed system allocates the same HVAC usage times to each household by segmenting households into a number of groups and allocating each group with sufficient power to operate either an AC or CO if sufficient power is available or power their CO or MF if the power is insufficient. The number of groups is directly related to the number of households, and thus the number of HVAC appliances of each type in the cluster, the level of surplus power available, the amount of basic set demand, and the time period to be covered directly set by the period of the OFF zone.

Figure 7.6 shows domestic demand undergoing a (4 × 2) cyclic blackout broken down into its two main components; basic set and interlocked HVAC provided to households on a one per family basis. The varying level of aggregated standby power and its effect on the HVAC demand is evident. It is worth noting the disappearance of the thermal payback phenomenon due to the previously mentioned assumption that ACs are set at full thermostat setting (maximum cooling), a typical social behaviour in badly insulated houses. In this figure the fair distribution of HVAC usage rights are calculated every hour which represent a different approach to the previously used on in which the fair distribution calculation is calculated at the beginning of each time zone which is the period along which the level of snooped power remains constant. The new approach checks the snooped power level every hour instead of the need to know the length of each time zone in advance throughout the day. On the other hand it produces shorter yet repetitive AC-CO assignments to households.

Figure 7.6 also presents an expansion of the bridged OFF zone 1, showing the fair share distribution of surplus power to 20 households in summer during a 4 × 2 cyclic blackout (4 OFF zones each 120 minutes long). During the first hour, the system has calculated that 2 ACs and 18 COs can be powered with the available power. The first hour is segmented into 10 time zones and during each zone, 2 of the 20 houses are granted AC usage rights whilst the remaining 18 houses are authorized to operate COs. To make the allocation fair, in each subsequent zone, 2 new households are authorized to operate their ACs; effectively the usage right moves from two households to the next two until all 20 houses are covered.

The situation changes during the next hour and due to a slight increase in the basic set demand, the available surplus power reduces and is now insufficient to power the same set of HVAC appliances. The system re-calculates the number and type of HVACs that can be powered; now only 1 AC and 19 COs can be supported. Each hour is thus segmented into 20 time slots and at each slot one AC and 19 COs are powered. The powered AC-CO mix is distributable evenly and fairly among the 20 households. If the available power indicates a usage rights allocation equivalent to 9 ACs and 11 COs, then the approach re-adjusts the mix to 5 ACs and 15 COs to ensure a fair distribution. This creates inefficiencies as some of the surplus power remains unallocated.

Figure 7.7 shows the relationship between the HVAC demand components and the surplus power level; to emphasize this relationship the basic set demand is excluded from the graph for clarity and thus all surplus power is dedicated to power HVAC demand only.

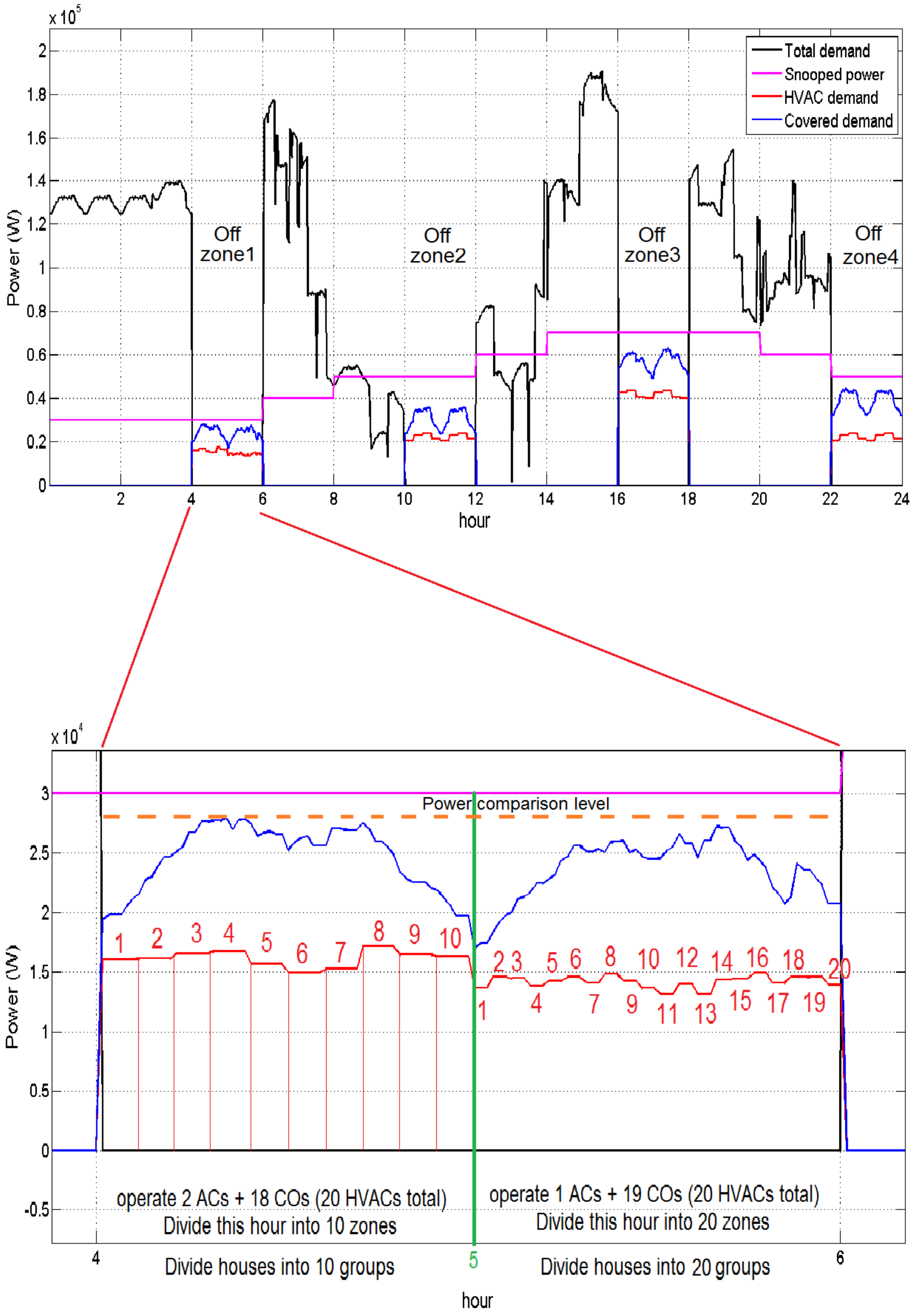


Figure 7.6: The bridging of demand.

In addition, it is assumed that bedroom ACs is used during the sleeping period (12-6 am) only, replaced by living room ones throughout the day. During low surplus power periods, as in Time Zone 1, the number of operational COs is high while the number of operational ACs is at its minimum. As the power level increases, the number of COs decreases and the number of ACs increases. If the amount of surplus power is sufficient to operate all ACs then the number of operational COs falls to zero, as seen in the Time Zone 7. Evident is the inversely proportional relationship between the number of active ACs and COs. There is a clear difference in the HVAC demand between each sub-zone owing to variations in the AC demand at each household. It is not assumed that all ACs have the same demand. This figure illustrates the existence of some unallocated (although there is a need for it, it could not be deployed) or unused (there is no need for it) generation capacity. These types of surplus power conditions can be treated either through electric energy storage or used in enhancing the level of air conditioning offered to customers through the allocation of additional ACs to houses in a fair way on a daily basis i.e. not based on daily sub-zones.

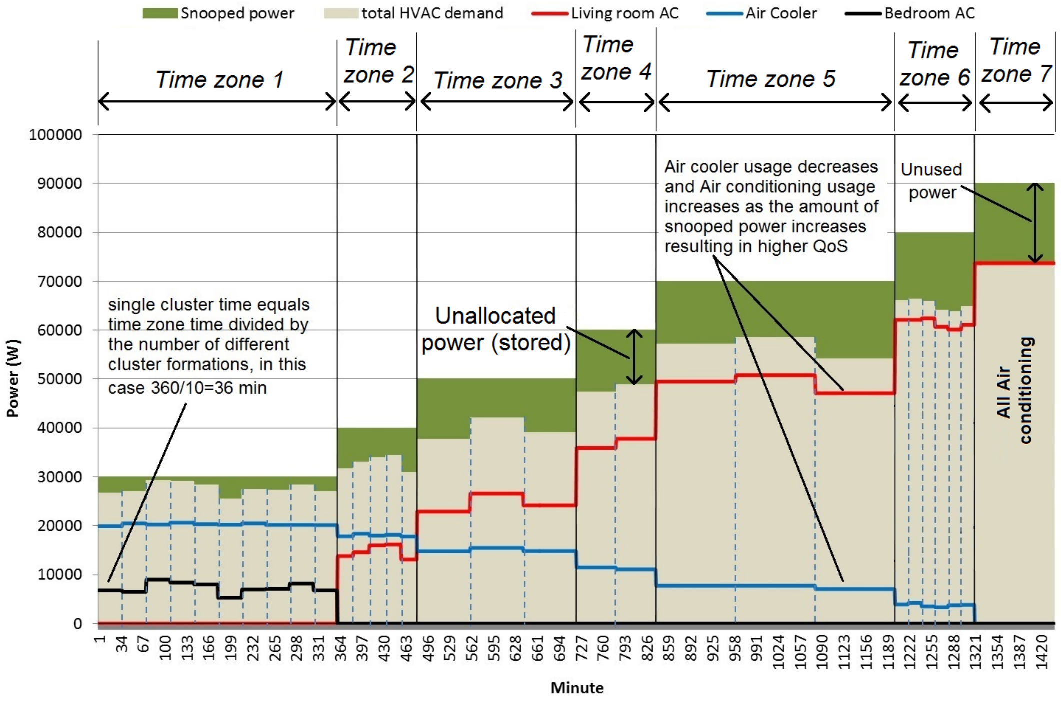
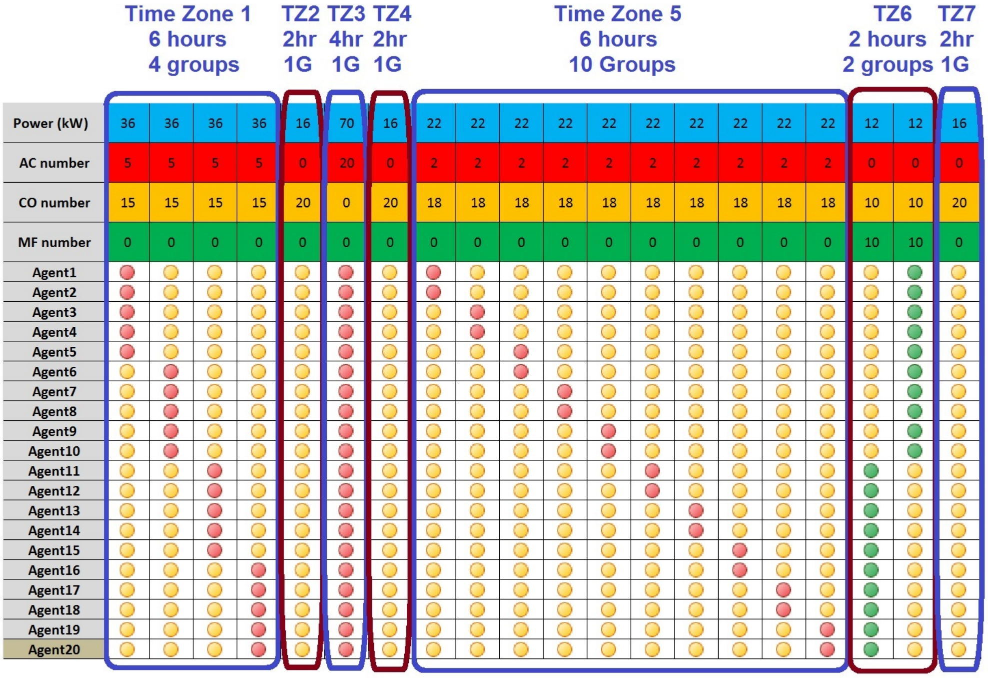


Figure 7.7: AC-CO-MF distribution.

Figure 7.8 shows the resulting fair share distribution over 20 households for AC-CO, CO alone, AC alone, and CO-MF combinations. Red circles represent ACs, yellow ones represent COs, and the green ones represent MFs. Every household has the same amount of usage time for each type of active HVAC appliances, independent of the amount of available surplus power or the type and combination of activated HVAC appliances. The figure also shows clearly that the reason for dividing each time zone into sub-zones is to allow each household to have the usage right of a certain HVAC appliance. It is evident that the distribution is fair and every household is allocated the same amount of usage time for each type of HVAC appliance depending on the amount of secured surplus power and the length of its availability at that level.



	Time Zone 1 6 hours 4 groups				TZ2 2hr 1G	TZ3 4hr 1G	TZ4 2hr 1G	Time Zone 5 6 hours 10 Groups										TZ6 2 hours 2 groups		TZ7 2hr 1G
Power (kW)	36	36	36	36	16	70	16	22	22	22	22	22	22	22	22	22	22	12	12	16
AC number	5	5	5	5	0	20	0	2	2	2	2	2	2	2	2	2	2	0	0	0
CO number	15	15	15	15	20	0	20	18	18	18	18	18	18	18	18	18	18	10	10	20
MF number	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	10	0
Agent1	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡
Agent2	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡
Agent3	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡
Agent4	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡
Agent5	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡
Agent6	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡
Agent7	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡
Agent8	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡
Agent9	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡
Agent10	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡
Agent11	🟡	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟢	🟡	🟡
Agent12	🟡	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟢	🟡	🟡
Agent13	🟡	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟢	🟡	🟡
Agent14	🟡	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟢	🟡	🟡
Agent15	🟡	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟢	🟡	🟡
Agent16	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟢	🟡	🟡
Agent17	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟢	🟡	🟡
Agent18	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟢	🟡	🟡
Agent19	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟢	🟡	🟡
Agent20	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟢	🟡	🟡

Figure 7.8: HVAC usage rights fair share distribution.

Table 7.2 shows the amount of available surplus power in each time zone, the calculated combination of HVAC appliances, the amount of unallocated power, and finally any re-adjustment to the calculated HVAC combination to ensure a fair distribution. In this case, only Time Zone 1 needed re-adjustment, since the original allocation produced AC=7, CO=13 and MF=0; post re-adjustment the allocation became AC=5, CO=15, MF = 0.

Table 7.2: Original and corrected composition and power of HVAC cluster.

No. of AC	No. of CO	No. of MF	Total HVAC	HVAC power (W)	Snooped power (W)	Power difference (W)	Status
7	13	0	20	33550	36000	2450	original
5	15	0	20	28250	36000	7750	Fixed
0	20	0	20	15000	16000	1000	original
20	0	0	20	68000	70000	2000	original
0	20	0	20	15000	16000	1000	original
2	18	0	20	20300	22000	1700	original
0	10	10	20	10000	12000	2000	original
0	20	0	20	15000	16000	1000	original
AC demand: 3400 W, CO demand: 750 W, MF demand: 250 W , Houses number: 20							

7.3.1.1 Unallocated surplus power problem

Of note is the issue of unallocated power i.e. the difference between the needed power to activate the selected combination of HVACs and the available surplus snooped power. Figure 7.9 shows the usage rights fair share distribution for seven different levels of allocated power, each time zone with its own HVAC combination. In this figure there are two types of superfluous power; unused and unallocated snooped power. The former is the power remaining after provisioning the optimum air conditioning service - by activating all ACs – a situation happens only when there is more power than needed e.g. Time Zone (23-24). The system has more power than needed to allocate ACs to all households, leaving the remaining surplus power unused. The latter is the power remaining after activating the calculated combination of ACs, COs, and MFs, expected every time the system calculates the mix of the HVAC adaptive cluster, a direct result of satisfying the “Fairness prioritisation” condition (Section 4.7.2).

The magnitude of superfluous power depends on the amount of surplus power and the number of beneficiaries. During the day, on occasions, the unallocated power is high as in the Time Zone (14-20) and small as in Time Zone (6-8). The main reason is

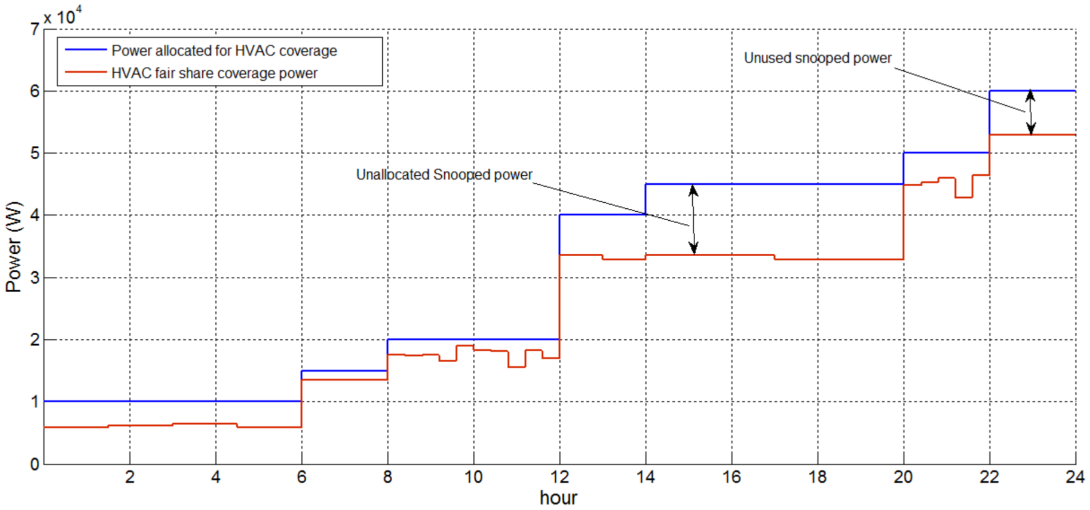


Figure 7.9: HVAC usage right, fair distribution for different power levels.

the dual nature of the HVAC adaptive clustering; in order to achieve the best fairly distributable HVAC adaptive cluster composition, the system initiates a two stage process. In the first, the best combination of ACs, COs, and MFs that can be supported by the available surplus power is calculated and during the second a fair allocation to various HVAC appliances among all beneficiaries is executed, subject to satisfying the conditions stipulated in Section 4.7.2. Table 7.3 shows the stages of the clustering decisions; the upper shows the outcome of the originally calculated cluster composition and the lower shows the calculations and adjustments needed to fairly distribute the HVAC appliances among all participants.

The main difference is the number of HVAC appliances calculated at each time zone. Five time slots have the same HVAC combinations (2, 3, 4, 6, and 7) while (1 and 5) are different. In Time Zone 1, the best HVAC set is AC= 0, CO=8 and MF = 12 and in Time Zone (5) the best is AC=13, CO=7, and MF=0. Both combinations are not fairly distributable; thus re-adjustment of the first into AC=0, CO=5, and MF=1 and the fifth into AC=10, CO=10, and MF=0 is made, in so doing some unallocated power remains. The re-adjustment loses 24%, 10%, 13%, 16%, 9%, 10%, and 12% during the identification of the best HVAC mix, and 41%, 10%, 13%, 16%, 25%, 10%, and 12% during the second. Thus the ‘Fair Share’ distribution method always leaves some unallocated and even unused power as a by-product of its operations.

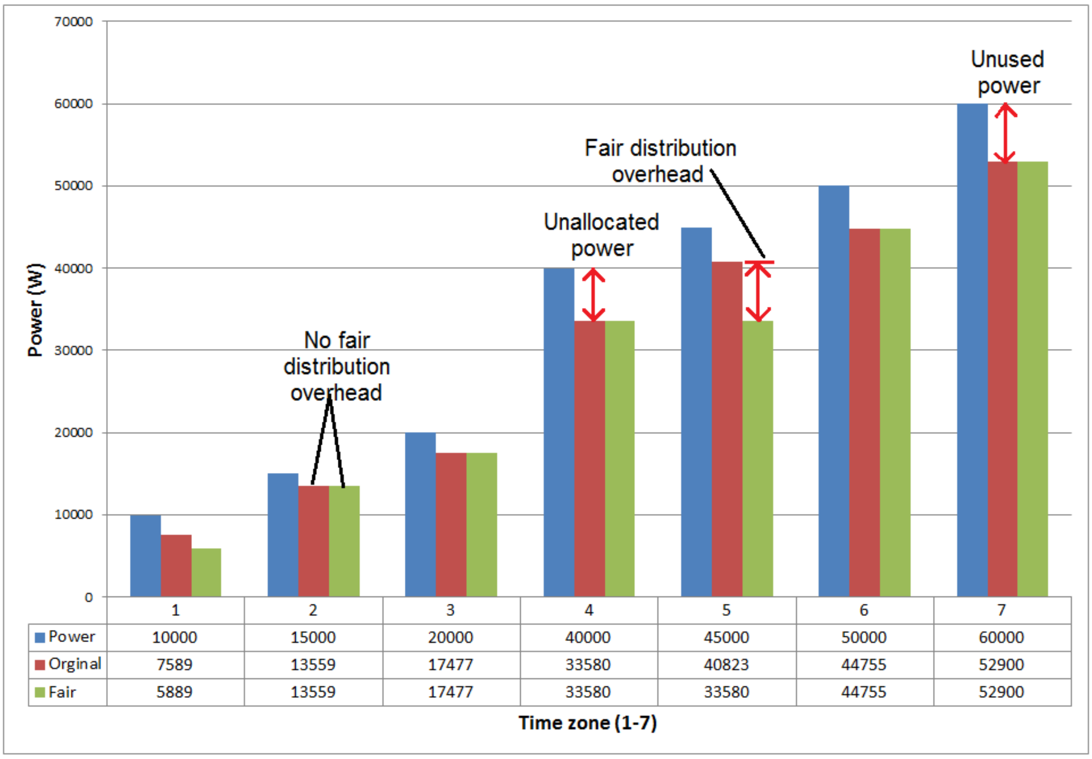
Table 7.3: Unallocated and unused power calculations

Original calculated HVAC cluster composition									
Power	**Original HVAC cluster composition**			**Total demand of each type**			**Total**		
	AC	CO	MF	AC	CO	MF	Total	Difference	%
10000	0	8	12	0	5368	2221	7589	2411	24
15000	0	20	0	0	13559	0	13559	1441	10
20000	2	18	0	5200	12277	0	17477	2523	13
40000	10	10	0	26500	7080	0	33580	6420	16
45000	13	7	0	35800	5023	0	40823	4177	9
50000	16	4	0	42300	2455	0	44755	5245	10
60000	20	0	0	52900	0	0	52900	7100	12

Fair share HVAC cluster composition									
Power	**Original HVAC cluster composition**			**Total demand of each type**			**Total**		
	AC	CO	MF	AC	CO	MF	Total	Difference	%
10000	0	5	15	0	3034	2855	5889	4111	41
15000	0	20	0	0	13559	0	13559	1441	10
20000	2	18	0	5200	12277	0	17477	2523	13
40000	10	10	0	26500	7080	0	33580	6420	16
45000	10	10	0	26500	7080	0	33580	11420	25
50000	16	4	0	42300	2455	0	44755	5245	10
60000	20	0	0	52900	0	0	52900	7100	12

Note: demand of individual appliances is not the same, each AC, CO, and MF has its own demand which is different, slightly or considerably, from the rest ones of its kind

Figure 7.10 shows the amount of unallocated power and its cause in each case. As is evident, there is unallocated power almost always but not always owing to the fair distribution principle.



	1	2	3	4	5	6	7
🟦 Power	10000	15000	20000	40000	45000	50000	60000
🟥 Orginal	7589	13559	17477	33580	40823	44755	52900
🟩 Fair	5889	13559	17477	33580	33580	44755	52900

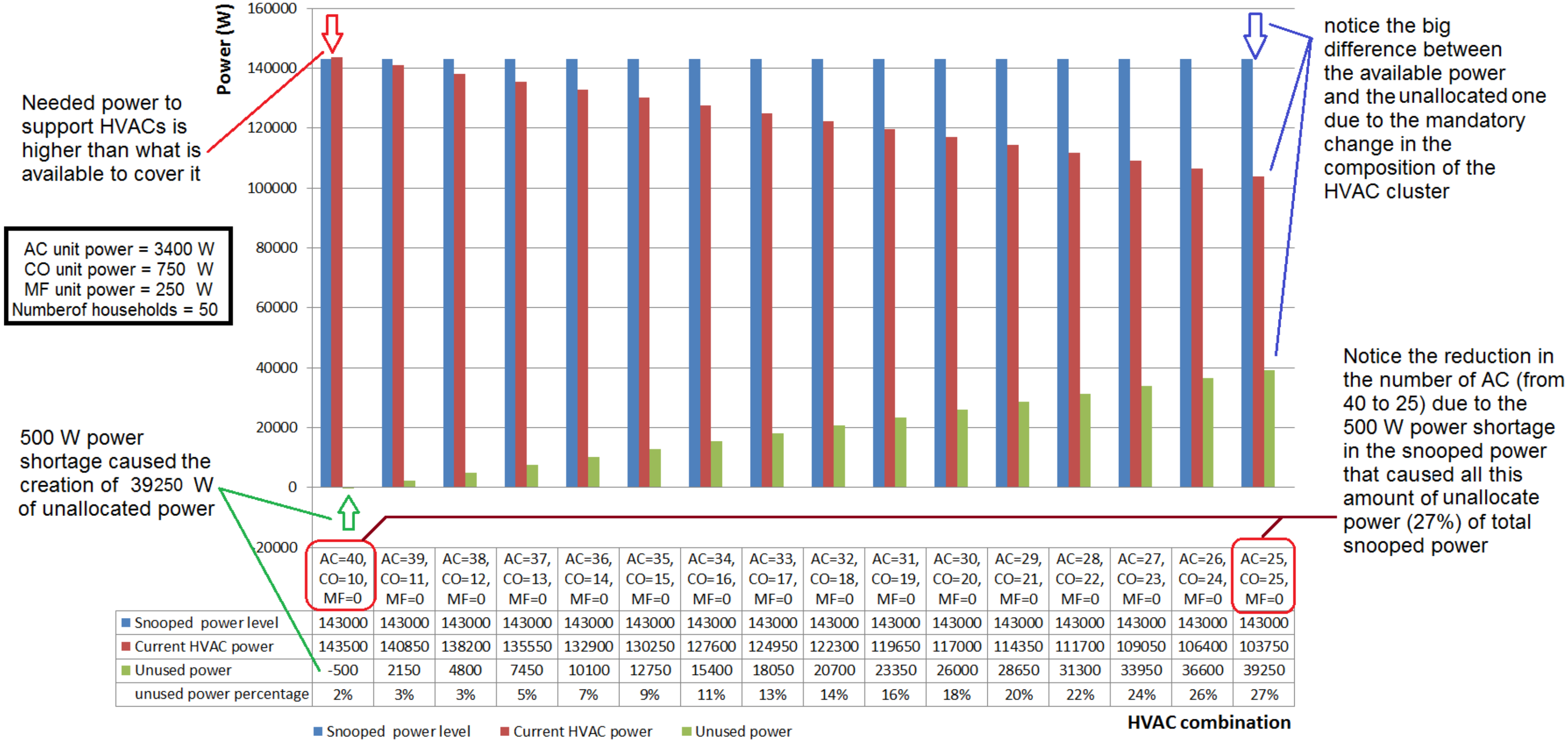
Figure 7.10: Original, fairly distributed, and the available snooped power.

7.3.1.2 Unallocated surplus power solution

In severe power shortage situations the waste of any amount of available power compromises the efficiency of the solution. As an example, Figure 7.11 shows the case of 50 households with a HVAC cluster composed of 150 HVACs. In this case and for the given surplus power, the mechanism is unable the allocate 40 ACs and 10 COs (marked by the red arrow on the far left side) fairly; the most fair allocation diminishes to 25 ACs and 25 COs (marked by the red arrow on the far right side) directly attributable to a 500 W shortfall in the amount of surplus power available for sustaining the clustered HVAC demand (143.5 kW). 27% (~39 kW) of the surplus power (~104 kW used) remains unallocated.

One approach to managing the unallocated power is to harness available battery storage facilities. Storing unallocated/unused surplus power and subsequently using it to compensate for any shortfall in the power needed to provide better air conditioning/cooling is a straightforward approach. For example this 500 W power deficiency mentioned in the scenario described above has prevented households from benefiting from 37.5% of the possible ACs that they could have, reducing the number of used AC from 40 to 25 despite the fact that almost sufficient power was available to support them. Reclaiming that 500W from battery storage supplementing the available power dedicated to support HVACs in the next phase increases the effectiveness of the solution. In this way the charge-discharge cycles yield benefits in recycling the unallocated and unused surplus power and using it to enhance fair share cycles and thus providing better air conditioning/cooling service to participating household.

In summary, the fair share HVAC distribution strategy has advantages and disadvantages; it distributes HVACs usage fairly but in its current version, on many occasions, leaves a considerable amount of valuable surplus power unallocated, compromising the ability to power more ACs.



Needed power to support HVACs is higher than what is available to cover it

AC unit power = 3400 W
CO unit power = 750 W
MF unit power = 250 W
Numberof households = 50

500 W power shortage caused the creation of 39250 W of unallocated power

notice the big difference between the available power and the unallocated one due to the mandatory change in the composition of the HVAC cluster

Notice the reduction in the number of AC (from 40 to 25) due to the 500 W power shortage in the snooped power that caused all this amount of unallocate power (27%) of total snooped power

	AC=40, CO=10, MF=0	AC=39, CO=11, MF=0	AC=38, CO=12, MF=0	AC=37, CO=13, MF=0	AC=36, CO=14, MF=0	AC=35, CO=15, MF=0	AC=34, CO=16, MF=0	AC=33, CO=17, MF=0	AC=32, CO=18, MF=0	AC=31, CO=19, MF=0	AC=30, CO=20, MF=0	AC=29, CO=21, MF=0	AC=28, CO=22, MF=0	AC=27, CO=23, MF=0	AC=26, CO=24, MF=0	AC=25, CO=25, MF=0
🟦 Snooped power level	143000	143000	143000	143000	143000	143000	143000	143000	143000	143000	143000	143000	143000	143000	143000	143000
🟥 Current HVAC power	143500	140850	138200	135550	132900	130250	127600	124950	122300	119650	117000	114350	111700	109050	106400	103750
🟩 Unused power	-500	2150	4800	7450	10100	12750	15400	18050	20700	23350	26000	28650	31300	33950	36600	39250
unused power percentage	2%	3%	3%	5%	7%	9%	11%	13%	14%	16%	18%	20%	22%	24%	26%	27%

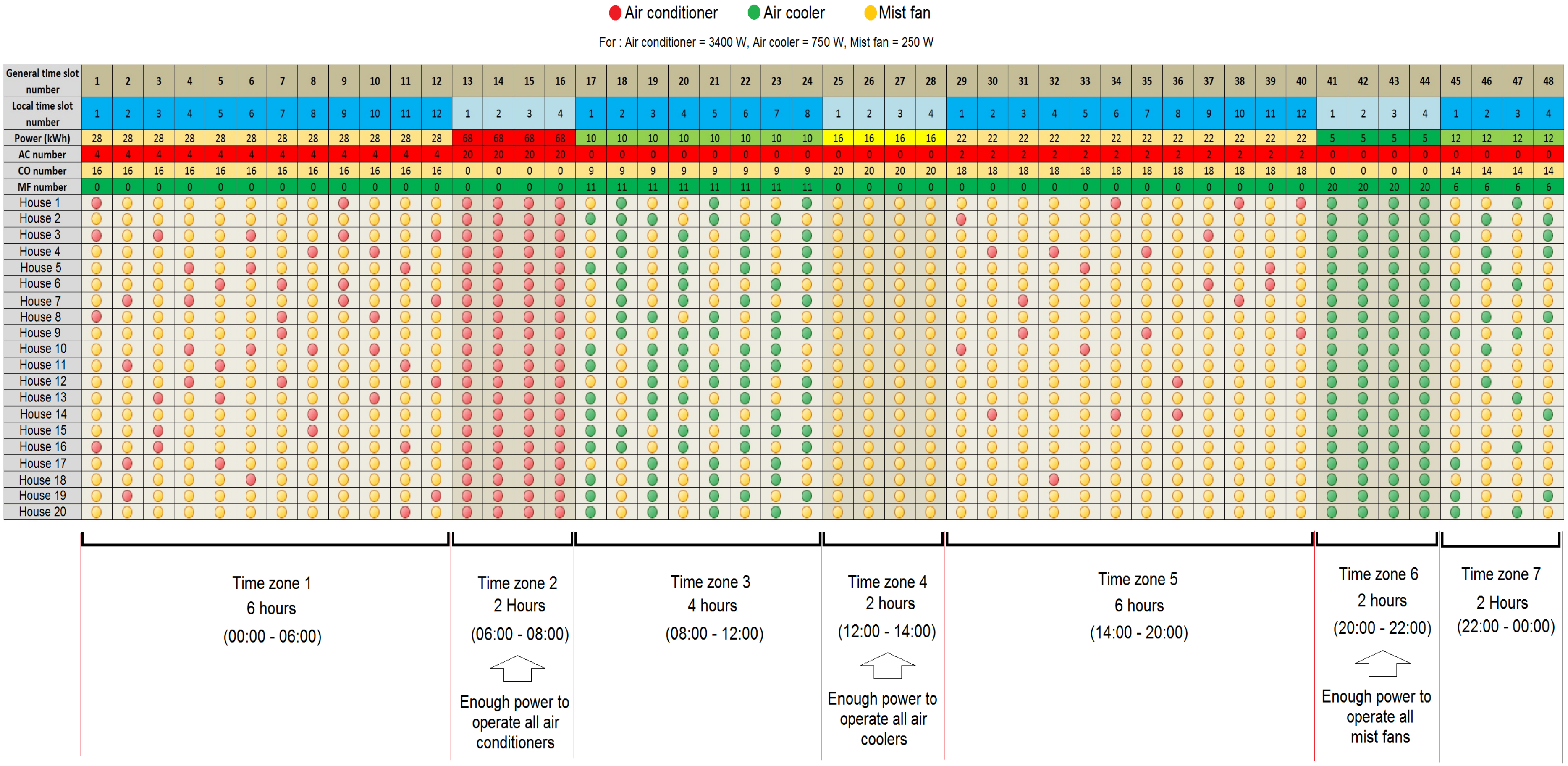
Figure 7.11: An example of a case of unallocated surplus power percentage for different AC-CO-MF combinations.

Note: these figures are just examples used to facilitate the unallocated power problem in the fair share distribution and are not derived by PANDA.

7.3.2 Temperature-triggered distribution

The temperature based usage rights distribution is based on allocating ACs to hotter houses, the cooler environments being serviced by COs if the available surplus power is sufficient to support an AC-CO pairing (or a CO-MF pairing if not). The mechanism is initiated by mapping the temperature of all houses every 30 mins and, based on the temperature, allocates the most effective HVAC appliances for hotter houses and the less effective to the remainder. The reason for selecting the 30 mins interval is to give dwellers reasonable time to benefit from the allocated high performance HVAC appliance - ACs in an AC-CO pairing or COs in a CO-MF pairing - since shorter periods makes them not effective and longer periods prevents others from benefiting from them for long periods of time. The regular update of temperature obviates the need for household re-grouping and reassignment, as happens with the fair share distribution.

Figure 7.12 shows the daily temperature-triggered HVAC allocation. Some households receive a lower AC usage right such as household 19 and household 20 owing to several possible reasons such as better house insulation, more responsible dwellers, lower number of children in the family, or better house location. In Time Zone 2, Time Zone 4, and Time Zone 6 the power is sufficient to only provide a single type of HVAC, thus in such cases all households are allocated the same air conditioning/cooling service despite their internal temperature, while in the remaining zones a mixture of HVACs are activated. In this distribution strategy, the number of ACs and COs (or COs and MFs), and whether it is dividable into fair share or not is irrelevant, the number of calculated appliances at each time zone shows a mix of distributable (Time Zone 1 and 5) and non-distributable (Time Zone 3 and 7) combinations. The first row in this figure shows that the day is divided in 48 zones each is 30 minutes long.



🔴 Air conditioner 🟢 Air cooler 🟡 Mist fan

For : Air conditioner = 3400 W, Air cooler = 750 W, Mist fan = 250 W

General time slot number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Local time slot number	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	1	2	3	4	5	6	7	8
Power (kWh)	28	28	28	28	28	28	28	28	28	28	28	28	68	68	68	68	10	10	10	10	10	10	10	10
AC number	4	4	4	4	4	4	4	4	4	4	4	4	20	20	20	20	0	0	0	0	0	0	0	0
CO number	16	16	16	16	16	16	16	16	16	16	16	16	0	0	0	0	9	9	9	9	9	9	9	9
MF number	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	11	11	11	11	11	11	11
House 1	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🟡	🟢	🟡	🟡	🟢	🟡	🟡	🟢
House 2	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟡
House 3	🔴	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🔴	🔴	🔴	🔴	🔴	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟢
House 4	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🔴	🔴	🔴	🔴	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟢
House 5	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🔴	🔴	🔴	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢
House 6	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🟡	🟢	🟡	🟢	🟡	🟡	🟢	🟡
House 7	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🔴	🔴	🔴	🔴	🔴	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟢
House 8	🔴	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🔴	🔴	🔴	🔴	🟡	🟢	🟢	🟡	🟢	🟡	🟢	🟡
House 9	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🟡	🟢	🟡	🟢	🟢	🟡	🟢	🟢
House 10	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🔴	🟡	🔴	🟡	🟡	🔴	🔴	🔴	🔴	🟢	🟡	🟢	🟢	🟡	🟢	🟢	🟡
House 11	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🔴	🔴	🔴	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟡
House 12	🟡	🟡	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🔴	🟡	🟡	🟢	🟡	🟢	🟢	🟡	🟢
House 13	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🔴	🔴	🔴	🔴	🟢	🟡	🟢	🟢	🟡	🟢	🟡	🟢
House 14	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟡
House 15	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🟢	🟢	🟡	🟢	🟡	🟢	🟢	🟢
House 16	🔴	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🔴	🔴	🔴	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢
House 17	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🟡	🟡	🟢	🟡	🟢	🟡	🟢	🟡
House 18	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟡
House 19	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🔴	🔴	🔴	🟢	🟡	🟢	🟡	🟢	🟢	🟡	🟢
House 20	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🔴	🔴	🔴	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟡

General time slot number	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Local time slot number	1	2	3	4	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	1	2	3	4
Power (kWh)	16	16	16	16	22	22	22	22	22	22	22	22	22	22	22	22	5	5	5	5	12	12	12	12
AC number	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0	0
CO number	20	20	20	20	18	18	18	18	18	18	18	18	18	18	18	18	0	0	0	0	14	14	14	14
MF number	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20	20	20	6	6	6	6
House 1	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🔴	🟢	🟢	🟢	🟢	🟡	🟡	🟢	🟡
House 2	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🟢
House 3	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟢
House 4	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🟢
House 5	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🟡
House 6	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟡
House 7	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟡
House 8	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🟢
House 9	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🔴	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟡
House 10	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🟡
House 11	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟡
House 12	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🟡
House 13	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟡	🟢	🟡
House 14	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟢
House 15	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟡
House 16	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟡	🟢	🟡
House 17	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟡
House 18	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟡
House 19	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟢
House 20	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟡

Notes:
1. It is assumed that there is no utility supply during the day
2. In this example the day is divided into 7 time zones with different sizes
3. Temperature check is repeated every 30 minute time slot, a day is 48 time slot
4. It is assumed that the surplus power level will stay fixed during the time zone period

Figure 7.12: Temperature-triggered HVAC allocation strategy over a full day.

Figure 7.13 illustrates the temperature-triggered HVAC allocation under 30 mins-repetitive re-clustering, executed irrespective of the time period length during which the surplus power is constant. After calculating the optimum HVAC combination at the start of the 30 mins period, the number of allocated HVACs remains fixed, without any re-adjustment. One of the strengths of the temperature-triggered strategy is its ability to keep the amount of unallocated surplus power at a minimum. The amount of unallocated power is less than that required to power a single AC in an AC-CO pairing (or a single CO in a CO-MF pairing) no matter how many ACs (or COs) participate. The difference in the consumed power in each sub zone is due to the difference in the demand of HVAC appliances in the targeted residential area.

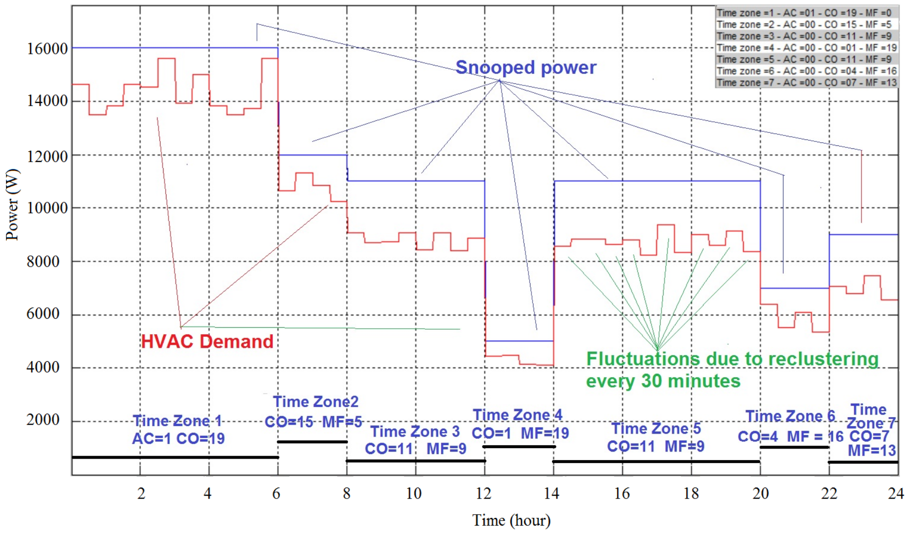
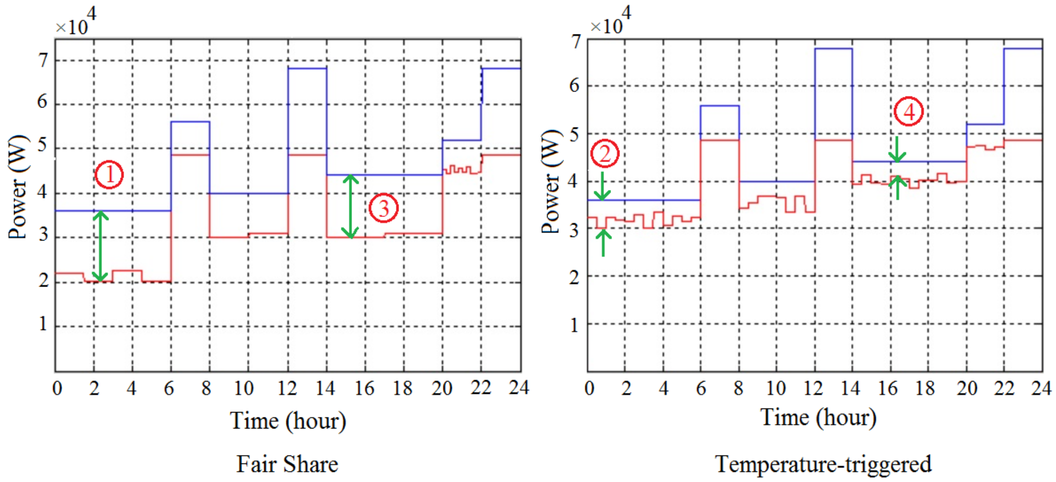


Figure 7.13: HVAC adaptive clustering under the temperature-triggered mode.

In order to prove that the temperature based strategy is efficient in utilising surplus power, Figure 7.14 compares the unallocated power in the two strategies; compare Time Zone 1 with 2 and Time Zone 3 with 4 and the difference in the amount of unallocated power is evident. On the other hand, time zones 6-8, 12-14, and 22-24 are flat as a consequence of having sufficient surplus power to provision all ACs. The performance of the temperature-triggered distribution improves as the number of households increases, while the fair share distribution performance continues to suffer from readjustment.



Fair Share

Temperature-triggered

Figure 7.14: Comparison between 'fair share' and 'temperature-triggered' HVAC usage right

In conclusion, the residential demand profile as experienced by the end user is presented in Figure 7.15. A continuous electrical supply is available; all essential BS appliances and at least one HVAC is operational 24/7, achieved without any modification to the already installed utility provision. An acceptable quality of life compared to the no power situation during the cyclic blackout scenario is achieved. The aggregation of surplus power from standby generation distributed coupled to the continuous monitoring of consumption allows the implementation of this approach.

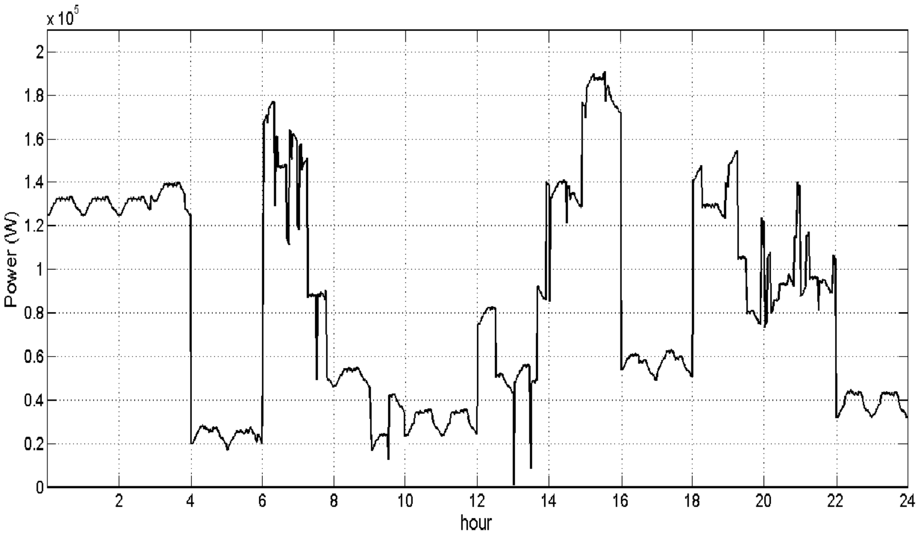


Figure 7.15: The final demand as experienced by the customer.

The temperature-triggered HVAC distribution has its downside since it is based on allocating ACs (i.e. more power) to hot, usually poorly insulated, houses and at the same time allocating less power to well-insulated ones (by providing them with COs). This scenario can be interpreted as punishing customers for proper behaviour and rewarding profligate customers for their poor practices.

7.4 Verification and Validation

Verification and validation of simulation related models and programs are important stages in the overall development process. [241] define verification as the determination that a simulation computer program performs as intended while validation is defined by [242] as proving that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model.

The verification of the approach to create the optimum HVAC cluster composition is considered first followed by the validation of its goal to provide all dwellings with an acceptable level of air conditioning. The first is executed by plotting the mechanism's performance trajectory and intersecting it with the available surplus power band, while the latter is executed by comparing the performance with WACLSS AC load shedding system proposed by [11].

7.4.1 HVAC Cluster Composition Verification

The process of calculating the optimum set of HVAC appliances to be powered from a certain level of surplus power is central to the cyclic blackout mitigation process. The verification is founded on inspection of the approach's performance trajectory (Figure 7.16). For the sake of symmetry and clarity, all ACs are assumed to consume the same demand, as are COs and MFs. Before exploring this figure, some terms need clarification:

Definition: The solution’s performance trajectory is the aggregated optimum HVAC cluster demand evolution curve covering all HVAC possible combinations ranging from the lowest (all COs in an AC-CO pairing scheme or all MFs in a CO-MF pairing scheme) to its highest (all ACs in an AC-CO pairing scheme or all COs in a CO-MF pairing scheme) HVAC sets.

Definition: The highest limit HVAC set is the cluster combination comprising of ACs only (in an AC-CO pairing scheme) or COs only (in a CO-MF pairing scheme). The power demand of such a set is highest among all possible HVAC combinations.

Definition: The lowest limit HVAC set is the cluster combination comprising of COs only (in an AC-CO pairing scheme) or MFs only (in a CO-MF pairing scheme). The demand of such a set is the lowest among all other possible HVAC combinations.

Definition: The coverage range is the range of demand generated by certain combinations of the HVAC pairing scheme ranging from the lowest to highest limit HVAC.

Definition: HVAC demand evolution is the calculated demand of a number of HVACs ranging from 0 up to its maximum population size of the same type.

Definition: Lower HVAC cluster is the cluster whose demand is the nearest, yet smallest, among all other HVAC clusters, for a certain surplus power level.

Definition: Upper HVAC cluster is the cluster whose demand is the nearest, yet largest, among all other HVAC clusters, for a certain surplus power level.

Definition: intersection demand is the HVAC demand at the intersection between the surplus power and the performance trajectory.

Definition: A surplus power band is the all (or part) of the surplus power dedicated to supply HVACs. The total demand of any calculated HVAC cluster combination should be as close as possible to this band yet it must not exceed its limit; if so, the cluster can't be powered.

This figure shows four graphs that are used to verify the operation of PANDA; the AC and CO demand evolution graphs, the available surplus power band, and PANDA's performance trajectory. The first two graphs represent the demand evolution for a number of HVAC appliances (ACs and COs in this case) ranging from 1 to 20 (the maximum number of houses under consideration). PANDA's performance trajectory is all the 'AC-CO' possible HVAC combinations available that can be powered while satisfying the 'provisioning of the best possible air conditioning' constraint which mandates the allocation of the maximum possible number of ACs in an AC-CO pairing scheme to households. Correct operation is verified if, for a certain surplus power level represented by the power band, PANDA provides the optimum AC-CO combination. This is assessed by defining a certain surplus power level and drawing its power band, (representing the level of available surplus power), drawing the AC and CO demand evolution graphs, obtaining PANDA's performance trajectory out of them, determining the intersection demand (located between the lower and upper HVAC cluster demands), and comparison with the demand of the HVAC cluster generated by the solution. The aim of this process is to determine if the latter is closest (smaller or equal) to the surplus power band. If the demand of the HVAC cluster generated is located outside the surplus power band then the HVAC adaptive clustering is erroneous. The trajectory also illustrates the difference between the AC and CO demand evolution profiles, resulting from the difference in their demands; shown clearly is the dominance of AC on the overall HVAC demand; the same observation can be made about the CO demand in a CO-MF pairing. AC and CO demand coverage ranges and their start and end limits are also shown.

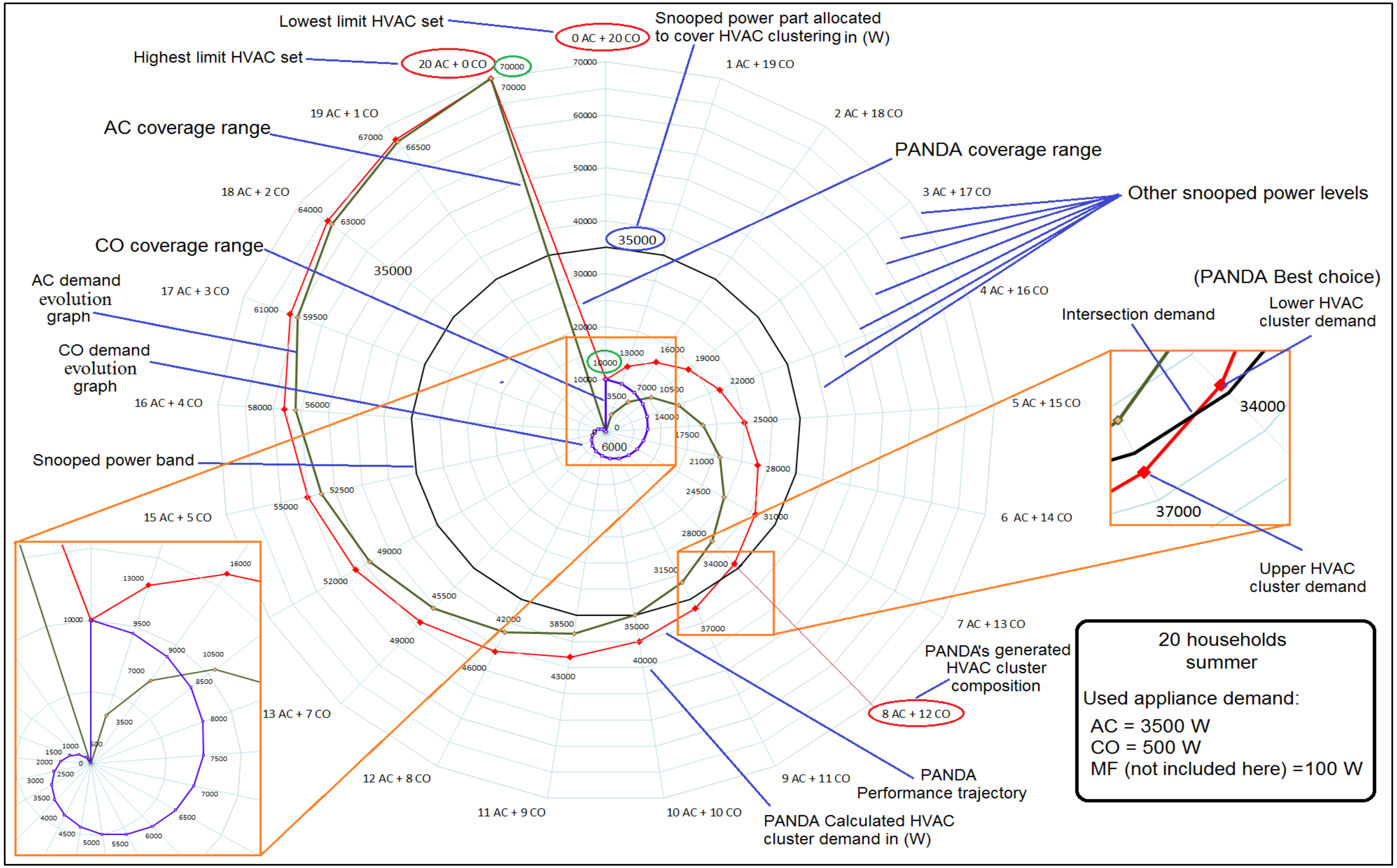
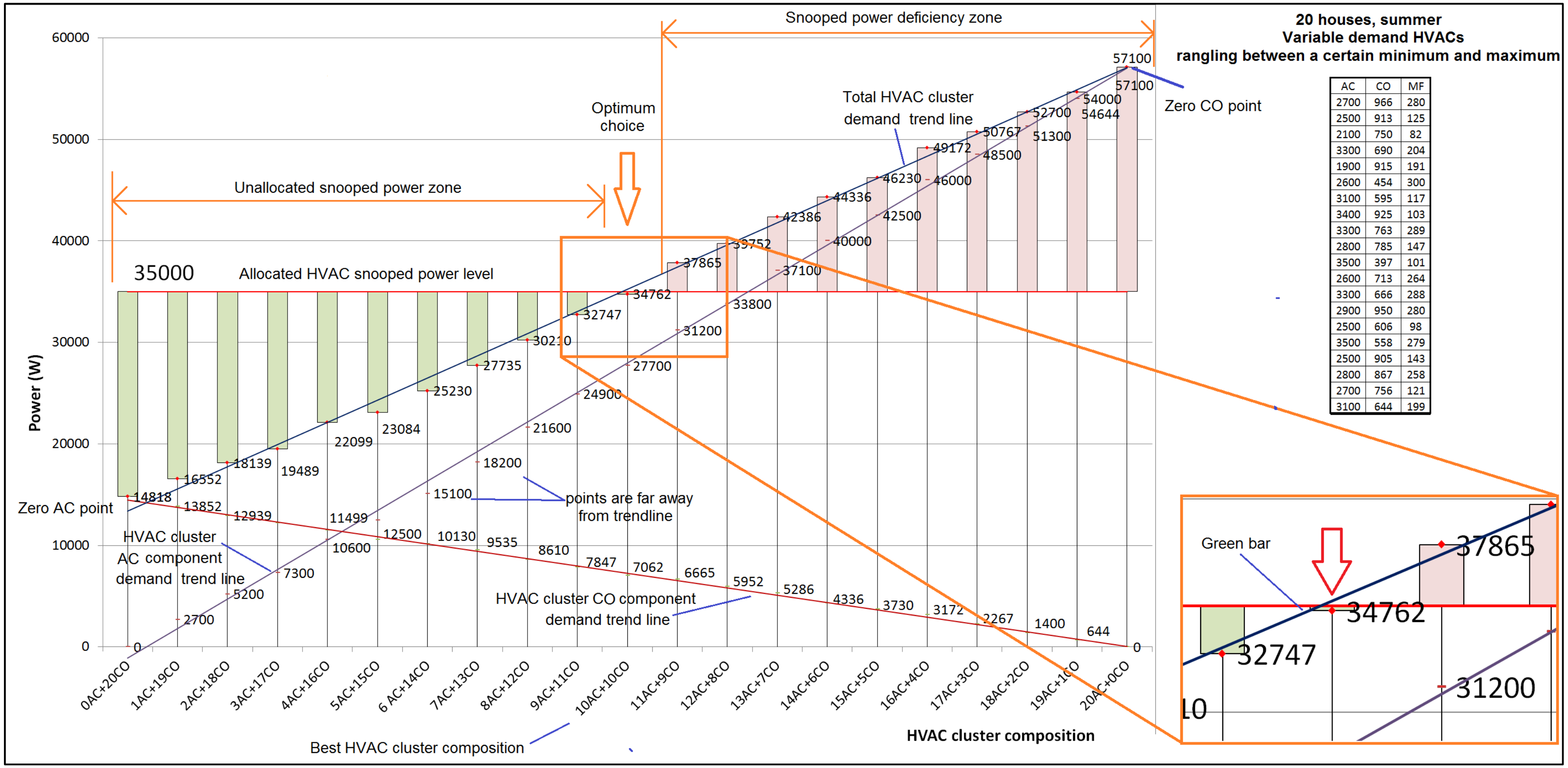


Figure 7.16: Performance trajectory for HVAC clustering.

It is worth noting that for the sake of symmetry, all ACs are set to have the same demand; the same is true for COs and MFs. Figure 7.17 shows the same verification process but using real AC, CO and MF demand profiles in addition to the unallocated power and power deficiency evolution patterns. Differences between these demands compared to their trend line are emphasized. AC and CO demand evolutions (drawn as trend lines) and actual AC, CO and MF demands are shown.

The two main zones on the performance trajectory (shown as straight lines) are illustrated; a substantial unallocated power zone (on the left) shows that for this amount of surplus power activating these AC-CO combinations will result in a significant level of unallocated surplus power due to the availability of a better AC-CO combination. The right zone pinpoints the AC-CO combinations unable to be supported due to a deficiency in surplus power.

A comparison of these results reveals a difference. In the former the optimum HVAC combination is AC = 8 and CO = 12 while in the latter the optimum HVAC combination is AC = 10 and CO =10; this is a consequence of the difference in the assumed ACs and COs appliance demands (fixed as opposed to diversified).



20 houses, summer
Variable demand HVACs
rangling between a certain minimum and maximum

AC	CO	MF
2700	966	280
2500	913	125
2100	750	82
3300	690	204
1900	915	191
2600	454	300
3100	595	117
3400	925	103
3300	763	289
2800	785	147
3500	397	101
2600	713	264
3300	666	288
2900	950	280
2500	606	98
3500	558	279
2500	905	143
2800	867	258
2700	756	121
3100	644	199

Figure 7.17: Variable power HVAC clustering mechanism performance analysis

7.4.2 Cyclic Blackout Mitigation Validation

[11] propose West-bank AC Load Shedding System (WACLSS, Section 3.7.4.5), a scheme for AC load shedding of groups of ACs through using local networked controllers that receive signals from a main controller and carry out air conditioning only load shedding operations without affecting the remaining household appliances. This represents the closest approach to the proposed scheme and is thus used for the purposes of validation.

Figure 7.18 captures the original result obtained by [11] showing two characteristics, the overall demand of Tulkarim city located in the west bank part of Palestine (red) and the managed version of the original demand (green). All ACs were clustered into ten groups and when the demand starts to exceed available supply, air conditioning load is shed, in one group steps, until a balance is reached between available supply and the managed demand.

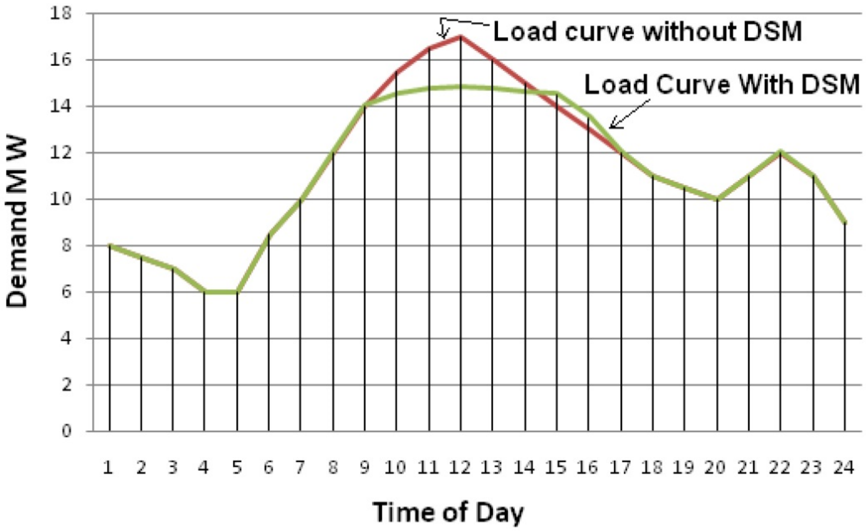


Figure 7.18: WACLLS results.

The bulge in the managed demand after the end of the peak period (between 14:30-17:30) is caused by the temperature payback phenomenon. The algorithm was implemented on the DDSM-IDEA platform and run on the Tulkarim city demand data obtained from the researcher himself [11]; the result of this implementation is shown in Figure 7.19.

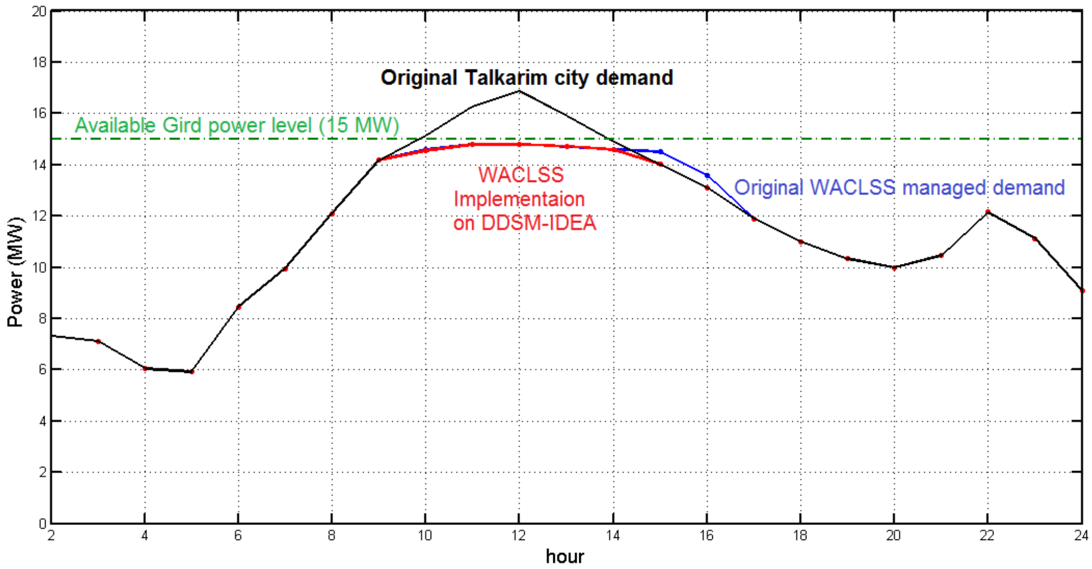


Figure 7.19: The implementation of the WACLSS algorithm on the DDSM-IDEA platform.

The implemented version is a good fit to the original except for the temperature payback factor, which was hard to implement on the platform which is originally generated by an expert system designed for this purpose. The WACLSS algorithm was then adopted to mitigate cyclic blackouts, through using the surplus power instead of the grid to power a population of ACs. In addition, the proposed solution coverage was plotted. The solution is shown to provide full HVAC coverage in a fair way over a wide range of surplus power starting always at the demand needed to sustain providing only MFs to all targeted households, For example, in the case of 20 houses each with 0.1 kW MF, the solution can provide full HVAC coverage for as low a surplus power of 2 kW. Figure 7.20 reinforces the flexibility to power all dwellings by providing one HVAC appliance per house regardless of level of available surplus power; the blue graph shows the amount of overall needed power to cover the selected HVAC appliance combinations. These results can be interpreted in terms of the QoE provided to households; as expected, the higher the available surplus power the better the air conditioning/cooling service.

On the other hand, WACLSS operates by grouping all the AC population into 10 groups and sheds these groups sequentially to keep demand within the limits of available supply. Thus during peak times the approach will never be able to provide full HVAC coverage. The situation is exacerbated as the power shortage increases.

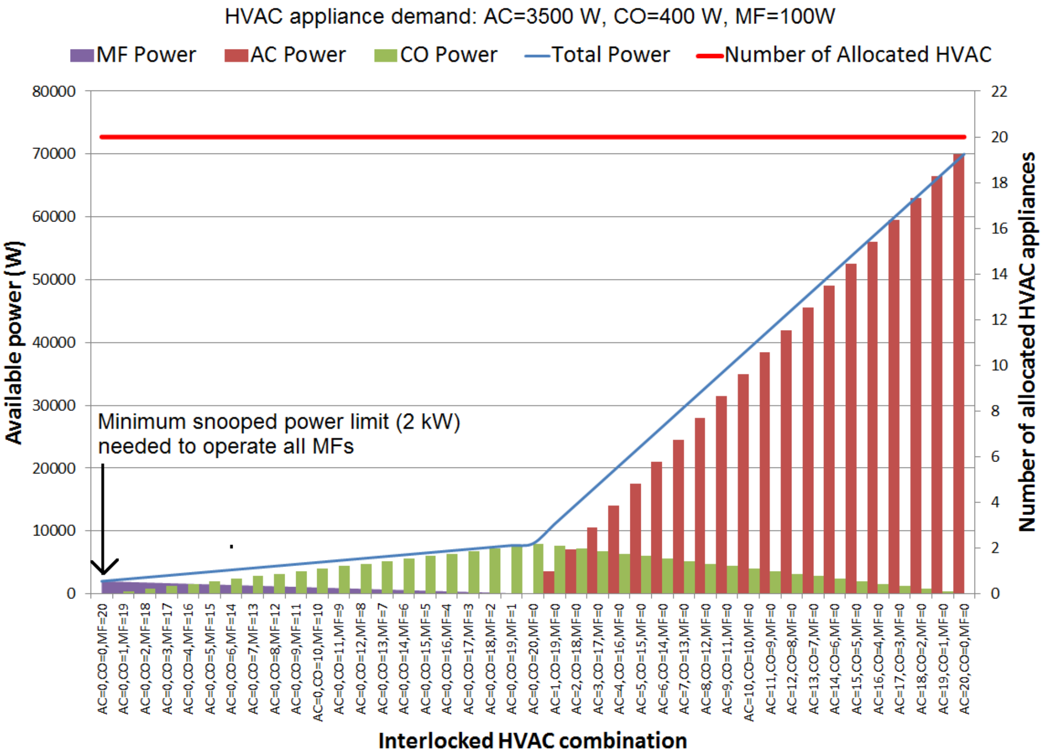


Figure 7.20: PANDA’s flexible power requirement for full HVAC coverage.

Figure 7.21 shows the coverage of the two techniques as a function of the level of surplus power. The ‘blue’ columns represent the number of operational ACs, the ‘red’ represent the number of operational COs, while the ‘green’ represent the number of operational MFs at every surplus power level. The dark ‘blue’ column represents the case when all ACs are enabled, the dark ‘red’ represents the case for all COs, and finally the dark ‘green’ represent all MFs. The figure also shows WACLSS AC coverage for the same surplus power levels. The ‘green’ dots connected by the horizontal line represent PANDA’s full coverage. WACLSS achieves full coverage once (at 70 kW) while the proposed solution achieved full coverage irrespective of the available level of surplus power. The versatility has its root in the latter’s ability to interlock a mix of HVAC appliances and power the most appropriate.

7.5 Comparison with other Techniques

In order to further assess the performance of the proposed approach and its merits, a comparison with similar techniques is presented. It is however worth remembering that the solution is targeting cyclic blackouts created by rotational load shedding. The solution relies on adaptive interlocking of clustered HVACs, a technique evolved from [132] termed 'Hybrid HVAC mode' related to determining the feasibility of operating large ACs and COs in tandem in large complexes. Compared to [132], PANDA has succeeded in:

- extending the usage of ACs and COs operating in hybrid mode to the residential sector
- introducing MFs to the original AC-CO pairing
- orchestrating the operation of a large population of ACs, COs and MFs
- providing a single HVAC appliance to each household in the residential area depending on the amount of harvested power
- has the potential to control not just air conditioning and cooling appliances but also space and water heaters using adaptive interlocking and clustering

[119] suggest empowering customers to control the operation of their AC appliances for the desired duration. The system identifies the number of ACs that can be operated and the duration of their operation according to the amount of utility power available and for the requested time of operation defined by the customer. The system then distributes ACs usage tokens among its customers informing each how long its AC can operate. The main difference between PANDA and this approach is that the former provides HVAC services to all customers while the latter permits some of the customers to operate their ACs for a restricted period of time, leaving the remainder without any air conditioning.

The proposed control of the AC demand through varying thermostats to a higher setting, [107], [114], [115] is not applicable in cyclic blackout scenarios since

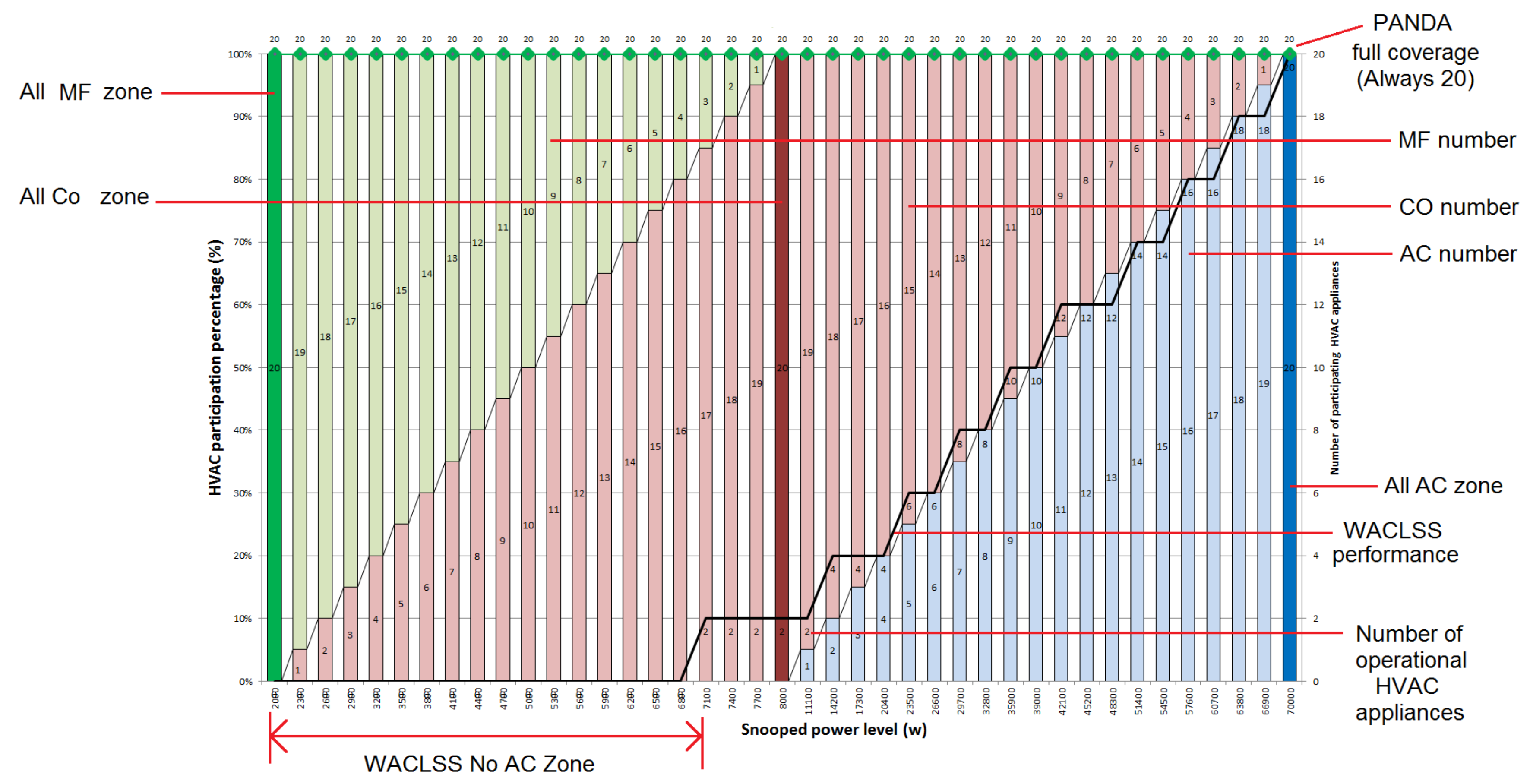


Figure 7.21: Air conditioning/cooling coverage in PANDA and WACLSS

sufficient continuous supply in needed to operate all participating ACs. In addition, the effect of raising the ACs thermostatic set point on the QoE worsen in hot weather if the change in the thermostat setting is large, otherwise its effect on the demand will be small if the change in the set point is kept small; in addition to that it needs a continuous supply of power needed to operate all ACs. Controlling AC fan speed [116] is not applicable in residential scenarios since it targets substantial central AC systems. The same is true for thermal storage [118], [103] applicable for big chillers used in large buildings. PANDA implements one major feature from 'PowerMatcher' [148] i.e. the principle of matching supply and demand which has proven to be an efficient technique through a series of evaluation studies [183], [184], [185], [186], [187], [188], [189].

The Intelligent Distributed Autonomous Power System (IDAPS) [169], [170], [171], and [172] utilises multi-agents in its implementation which addresses the problem of securing power through the utilization of customer-owned DG to fully support critical loads during outages and leaving surplus to power non-critical loads, so it is a load shedding based system. The Flexible, Reliable and Intelligent Electrical eNergy Delivery System (FRIENDS) [194], [195], [175], [199], [196] and [197] consists of Quality Control Centre hosting standby generation, control, and communication infrastructure provides power at multi-quality levels during power outages. PANDA, unlike FRIENDS, does not rely on substantial investment to acquire expensive standby generators since it harnesses surplus power from underutilised standby generation and at the same time provides the best possible power quality to its customer base. PANDA requires a number of additional infrastructure elements for full implementation since it relies on using dispersed standby generation and the LVDN and operates by switching power between the grid and the standby generators such as synchronization equipment, contactors, a main system controller, house local controllers. The Rokkasho village project uses substantial battery storage to compensate for fluctuations in the generated power by a nearby wind farm. The main difference is that the project relies on normal operational conditions, i.e. there is sufficient but fluctuating power.

7.6 Summary

Cyclic blackouts plague many countries hindering their development and forcing people to live under restrictions, especially in hot countries. The aim of the solution is to develop a methodology harnessing under-utilised standby power generation already in existence and aggregating their surplus power in order to provide a stream of power sufficient to support a basic set of appliances and one out of three (in the current version) different demand different performance interlocked HVAC appliances whose type is set depending on the amount of aggregated surplus power. The judicious powering of the appropriate HVAC appliance clustered in a combination can provide an acceptable QoE level. The result of implementing the proposed solution, verification of its functionality and the validation of its effectiveness has been presented. Results show that the solution has succeeded in providing a level of cyclic blackout mitigation with the ability to power a basic set of appliances and one (interlocked) HVAC appliance whose type is limited only by the amount of available surplus power.

The basic set appliances are not fixed and can be set as needed; fridges and freezers are the main contributors to the basic set demand. Air conditioning demand is the dominant contributor to the total demand; the basic set represents a small fraction of the total. Two HVAC appliances usage rights strategies are presented i.e. fair share and temperature-triggered. In the former, each house is granted the usage right to operate each type of HVAC appliance for the same length of time, while in the latter hotter houses are allocated ACs and the cooler COs within an AC-CO pairing (or COs and MFs in a CO-MF pairing).

The fair share distribution can result sometimes in significant amounts of unallocated power which rises as the number of households increases. Incorporating battery storage in the system compensates for such shortfalls or alternatively using this unallocated energy to enhance the air conditioning provision to customer in a fair way by activating more ACs. Temperature-triggered usage rights results in the maximum deployment of available surplus power. The HVAC cluster composition process is verified and system performance is compared with total and with AC only load shedding. The proposed approach performs well in comparison to reported schemes and has the ability to provide different degrees of air conditioning or air cooling to all households in a structured manner.

Chapter Eight
Extended Applications of Adaptive HVAC Interlocking

8.1 Introduction

The potential of adaptive HVAC interlocking has been proven to manage demand efficiently under a non-predictable supply providing a good QoE level during cyclic blackouts. In this chapter the potential of the technique is extended to the prevention of cyclic blackouts. The effect of changing the shape of the utility supply from its conventional cyclic ON/OFF to a continuous limited one is investigated, testing this robustness under multiple conditions and environments. The limitations and sensitivities of the approach are discussed and potential solutions are developed.

8.2 Cyclic Blackouts Prevention

Cyclic blackouts are natural effects of rotational load shedding, a well-known widely-used power shortage mitigation technique. During the course of development of the proposed solution, the level of available electricity supply is assumed to be at its minimum since the core of the technique relies on the utilisation of surplus power from distributed standby generation. This solution is considered to be temporary until sufficient utility power can be deployed e.g. establishing additional core generation capability.

In general, the main challenge that nearly every power system suffers from is covering peak demand. Thus the concept is extended to test if it has the ability to manage peak demand without severely affecting the customer QoE.

In the cyclic blackout prevention mode, PANDA is deployed essentially in the framework but with the following differences:

- power is supplied by the utility solely and not from nearby standby generation facilities
- the maximum permissible power level is kept constant at all times, thus there is no fluctuation in the supplied power level
- the minimum level of air conditioning for each household is not a requirement; a minimum reduction in some of the air conditioning demand is scheduled so that the overall demand doesn’t breach the utility capacity threshold
- adaptive HVAC interlocking is not applied to all houses but to a subset according to two criteria; the first is referred to as the HSF which is the number of people served by a single AC in a certain house and the HTUP which is the length of the time period during which that AC is kept operational.

In the cyclic blackout prevention mode, the system monitors the total demand of the targeted residential area and when it reaches the supply threshold, the replacement of a minimum number of living room ACs with their interlocked COs, on a one per house basis, is initiated. The operation continues until all living room ACs are exhausted. If the power shortage persists, bedrooms ACs are switched OFF as needed until the power gap between available supply and the total demand is closed. Otherwise guest room ACs are targeted. The system calculates the number of ACs to be turned OFF as needed and replaced with COs and the number of remaining ACs are turned OFF, applying this principle to all targeted ACs and COs at the same time.

8.2.1 AC Selection Criteria

The goal is to turn a minimum number of ACs OFF, grouped according to the type of room they are located in on a one per house basis, and replacing the ones located in the living rooms only with their interlocked COs as needed during peak time. The process follows certain selection criteria which are obviously fair from a customer perspective, closely linked to minimising the degradation in the air conditioning QoE level offered to the customer. Two AC selection criteria are proposed:

1. **HVAC Service Factor:** is the average number of individuals served by an AC in a certain household. The system preferentially turns OFF ACs with low HSF thus minimising the number of individuals affected by the reduction in the air conditioning QoS. The HSF is simply:

$$\text{HVAC Service Factor} = \frac{number\ of\ family\ members}{Number\ of\ operational\ ACs}$$

Figure 8.1 shows the calculated HSFs for 20 households.

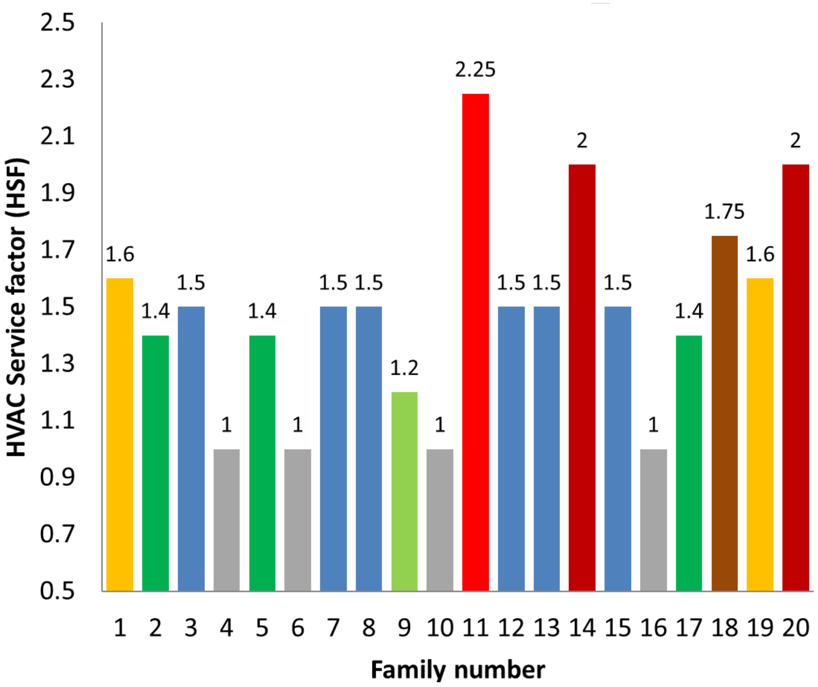


Figure 8.1: The HSF for 20 households.

2. **HVAC Total Usage Period:** is the total number of operating hours of a certain AC located in a certain room. For households comprising more than one room of the same type, the total number of working hours of all ACs in all those rooms is calculated. This criterion gives a clear indication of how long each AC is used; the system turns OFF and replaces ACs that have been operational for the longest periods. This approach makes good use of the

thermal storage of the targeted rooms and turns OFF colder environments first.

Figure 8.2 shows the HTUPs for 20 households. It is worth noting that all bedroom ACs are totalled making it easier to compensate for the difference between households in respect of the number of bedrooms. Another essential thing to note is that ACs located in different rooms with similar usage periods does not imply the same number of rooms of each type. For example in figure 8.2, the usage period of the living and bedroom ACs in some houses are nearly the same (houses 4, 9, 14, 16 and 20 (illustrated more clearly in Figure 8.3) but does not imply that the number of living and bedrooms in these houses are the same; it just means that their total usage periods are nearly equal.

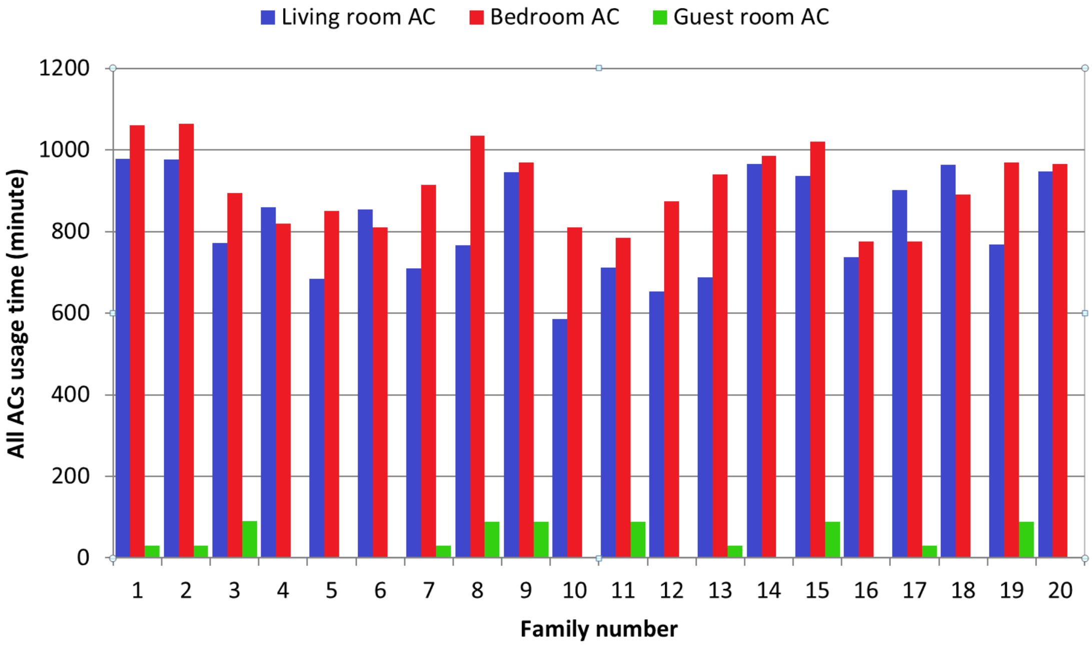


Figure 8.2: The HTUP for 20 households.

The same figure shows the small contribution of guest room ACs to the overall demand, the reason why they are left to the end of the prevention process. The bedroom AC is the dominant segment of the consumption profile since normally there is more than one bedroom in every house; however the living room AC demand is the most dominant among all ‘single’ rooms due to usage.

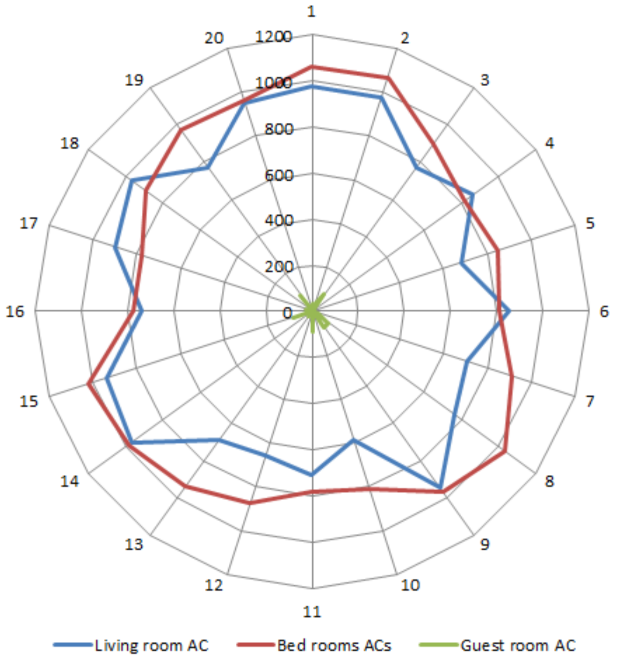


Figure 8.3: HVAC total usage period for 20 houses during summer.

Radial axis is the number of working hours and the circular one is house number

8.2.2 Peak Clipping

In this section the results of the cyclic blackout prevention process are introduced and discussed. The summer demand of a typical community consisting of 20 households is used for the validation and a range of utility power levels are used as test thresholds.

Figure 8.4 shows the effect of replacing only the living room AC with its interlocked CO based on HSF in order to highlight the need for AC load replacement for more than one room in each house which is needed if the available power is below a certain level, 120 kW in this case, despite the fact that such a measure is capable of reducing the peak demand by 20% (∽40 kW). The 120 kW, which represents the available supply, is shown for comparison.

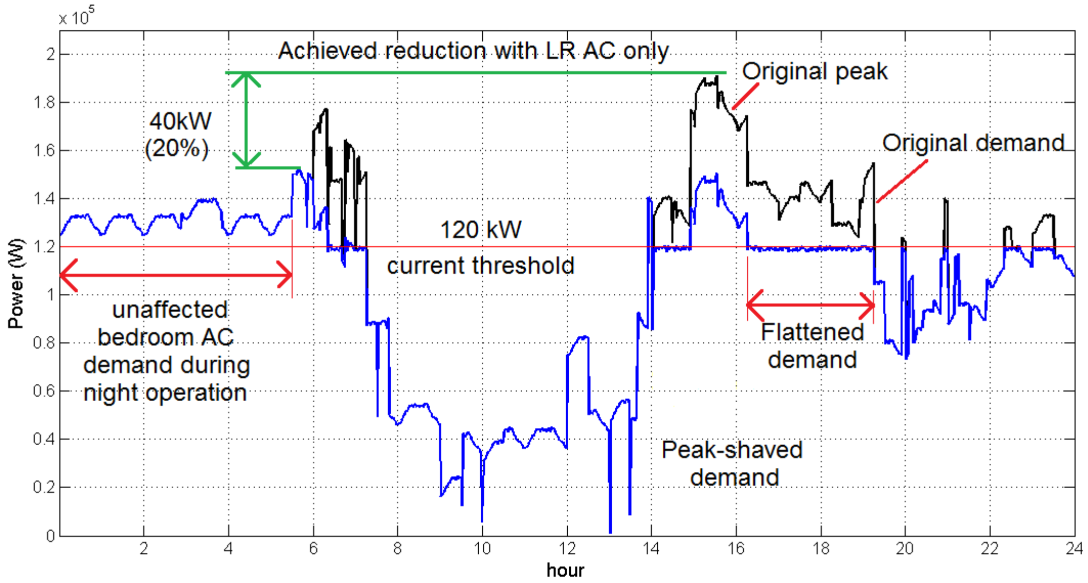
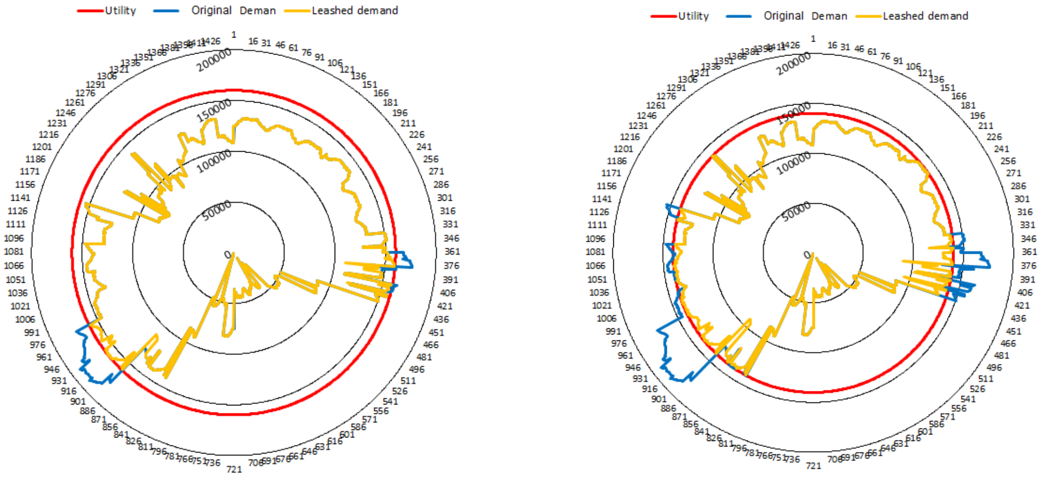


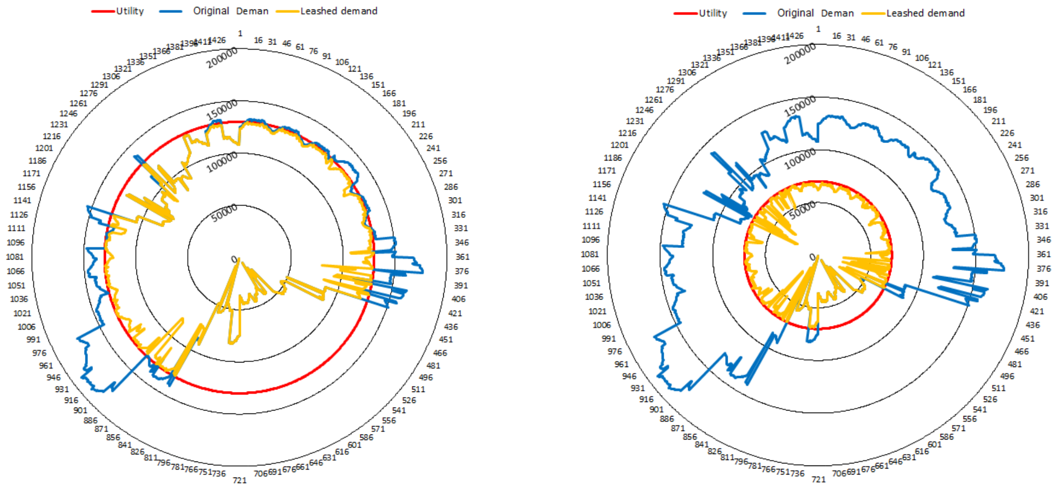
Figure 8.4: The effect of replacing the living room AC only by a CO on the overall summer demand of 20 households.

The night period has not been affected by AC-CO replacement (00-06 am), since during this time of the day only bedroom ACs are operational and living room ones are not. The demand of period 16 to 19 is flat, showing that replacing the living room AC with a CO is highly effective. The same observation can be drawn for the remainder of the evening period (up to hour 24). The necessity to turn OFF more than one AC in different rooms - bedroom AC during the night, living room during the day and evening, and if necessary using the guest room AC - is reinforced. Using only one AC (living room) is insufficient to prevent cyclic blackouts unless the power shortage is within 20% (in this case) of the maximum peak demand. This percentage is not fixed and is highly implementation dependent.

Figure 8.5 shows prevention responses as a function of utility power levels based on HSF; the ‘blue’ is the original demand, the ‘yellow’ the smoothed demand and the ‘red’ circle is the current utility level. The system has controlled the demand irrespective of the utility level. Figure 8.5(a) is for a utility power level of 160 kW (~84% of peak demand), the peak is clipped and the demand is stable within certain boundaries; Figure 8.5(b) is for a utility power level to 140 kW (~73% of the peak demand).



(a) 160 kW utility limit (b) 140 kW utility limit



(c) 130 kW utility limit (d) 70 kW utility limit

Figure 8.5: Prevention as a function of utility limits (a) 160 kW, (b) 140 kW, (c) 130 kW, and (d) 70 kW. The circular axis is the time in minutes and vertical is the power in Watts.

PANDA reduces the demand to match the limit. Figure 8.5(c) shows that a further reduction in the utility power level to 130 kW (~ 68% of the peak) widens the clipping to other areas within permissible limits. Finally Figure 8.5(d) shows that for a severe power shortage (a utility power level of 70 kW, ~37% of the peak demand), the system performance still manages demand within the available utility permissible power limits. These results also reveal the potential and effectiveness of HVAC interlocking when utilized in residential demand management. The control is executed without interfering with the usage of any other appliance and maintaining, by and large, an acceptable air conditioning level. As the grid power degrades to a lower level, the number of replaced/shed ACs increases which in turn degrades the level of air conditioning provision i.e. one of the ACs is replaced by a CO.

Careful examination of Figure 8.6 to Figure 8.9 aids in the deeper understanding of the process. In these figures the original demand, the managed demand, the available utility power level, living room AC interlocking, the maximum power saving using living room ACs only, and bedroom AC shedding is shown.

Figure 8.6 shows the case when the available utility power level is reduced to 160 kW (16% reduction in the utility power compared to peak demand), the coverage of the power shortage is executed mainly by interlocking part of the living room AC with their CO counterparts supported by a low number of bedroom ACs sufficient to

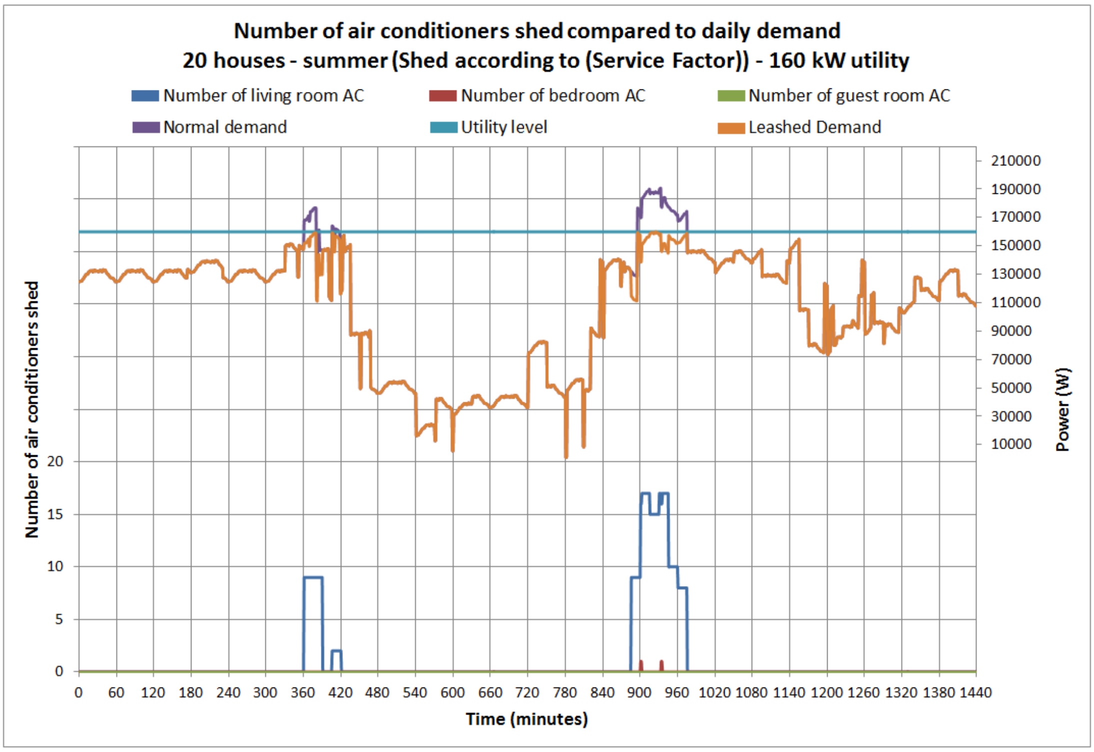


Figure 8.6: A comparison between the original summer demand of 20 houses and the number of AC replaced and shed in different rooms during a cyclic blackout HSF-based prevention for a 160 kW utility power level.

match the shortage in the supplied utility power. If the power shortage becomes more acute, additional living room ACs are replaced by their interlocked COs and the number of bedroom ACs shed increases (Figure 8.7, the available power is reduced to 140 kW). The dependency on the bedroom ACs has increased and since the living room ACs are interlocked with COs, the only ACs shed are in the bedrooms. The QoE remains acceptable while the system covers a ~26% reduction in the supplied utility power.

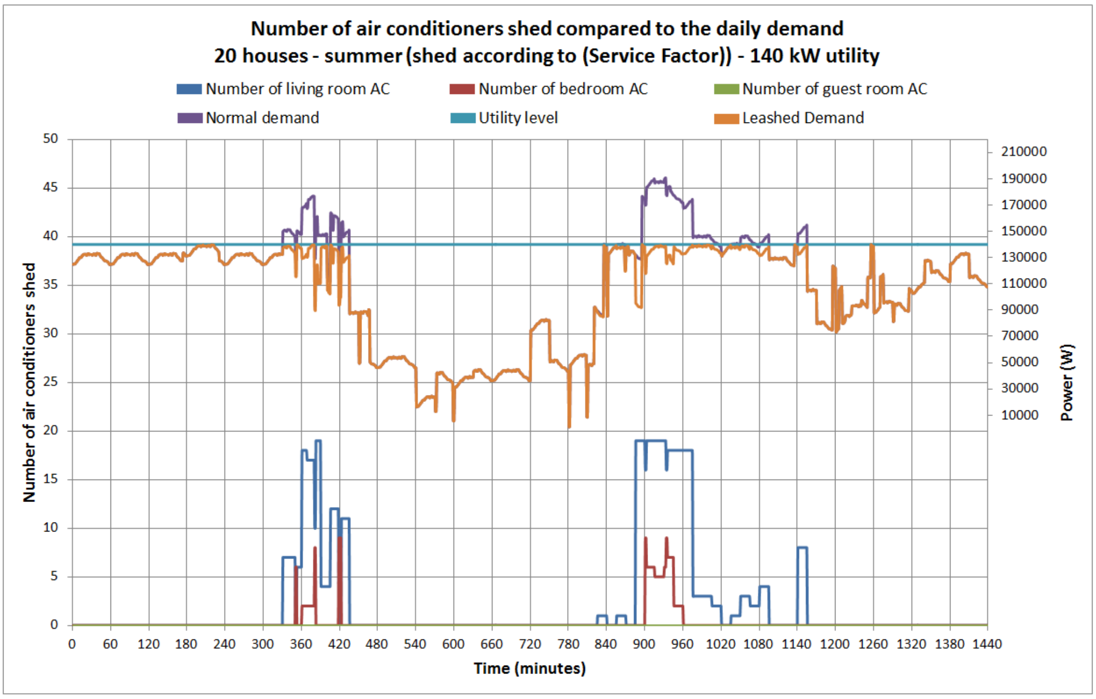


Figure 8.7: A comparison between the original summer demand of 20 houses and managed demand and the number of AC replaced and shed in different rooms during a cyclic blackout HSF-based prevention for a 140 kW utility power level.

Figure 8.8 shows the process as the power shortage increases i.e. the supplied power level drops to 130 kW. In response, the number of living and bedroom ACs shed increases, especially at night during the period between (00:00-5:30 am) when the living room ACs are normally turned OFF and all AC load shedding concerns bedrooms ACs.

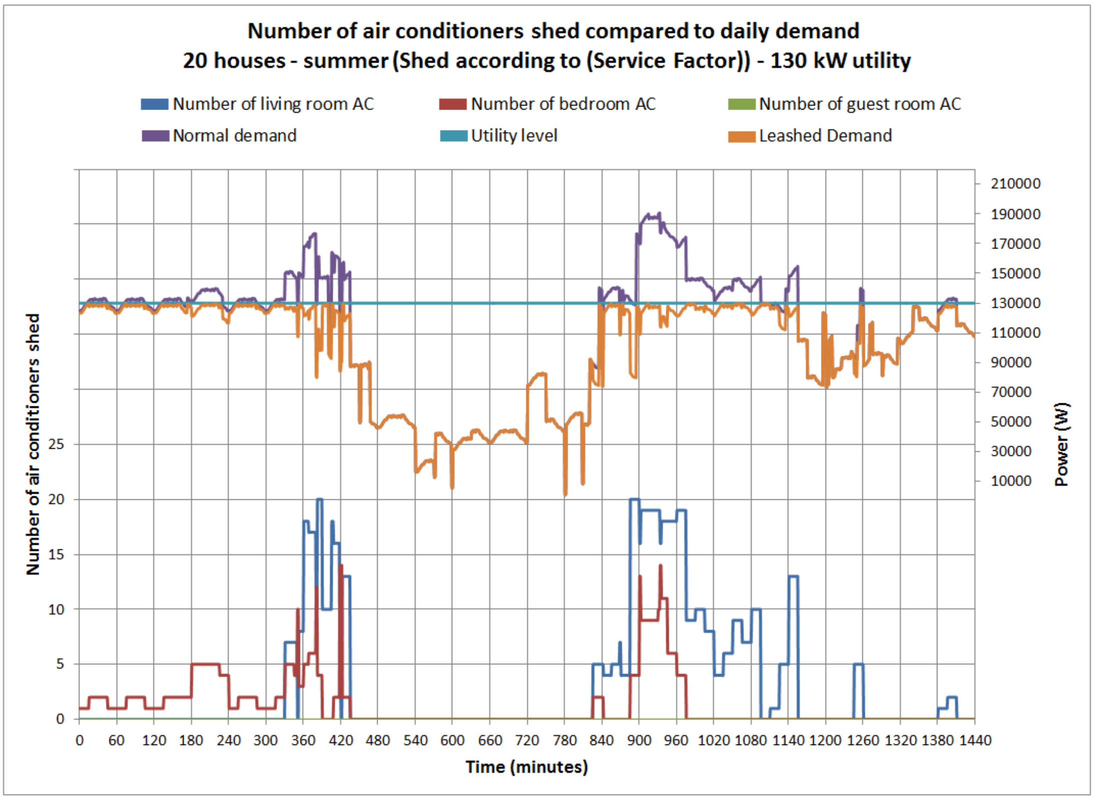


Figure 8.8: A comparison between the original summer demand of 20 houses and managed demand and the number of AC replaced and shed in different rooms during a cyclic blackout HSF-based prevention for a 130 kW utility power level.

As the supplied utility power drops to 70kW (Figure 8.9), the number of shed bedroom ACs becomes much larger; however COs are operational in the living room at each house in addition to some bedroom ACs.

So, in conclusion the system has managed to cover a wide range of power shortage levels. Interlocking an AC with a CO provides the ability to reduce the demand significantly without significant degradation of the air conditioning QoE. If the utility limits degrade to serious low levels, the system has the ability to operate COs only and works in a similar mode as in the mitigation mode.

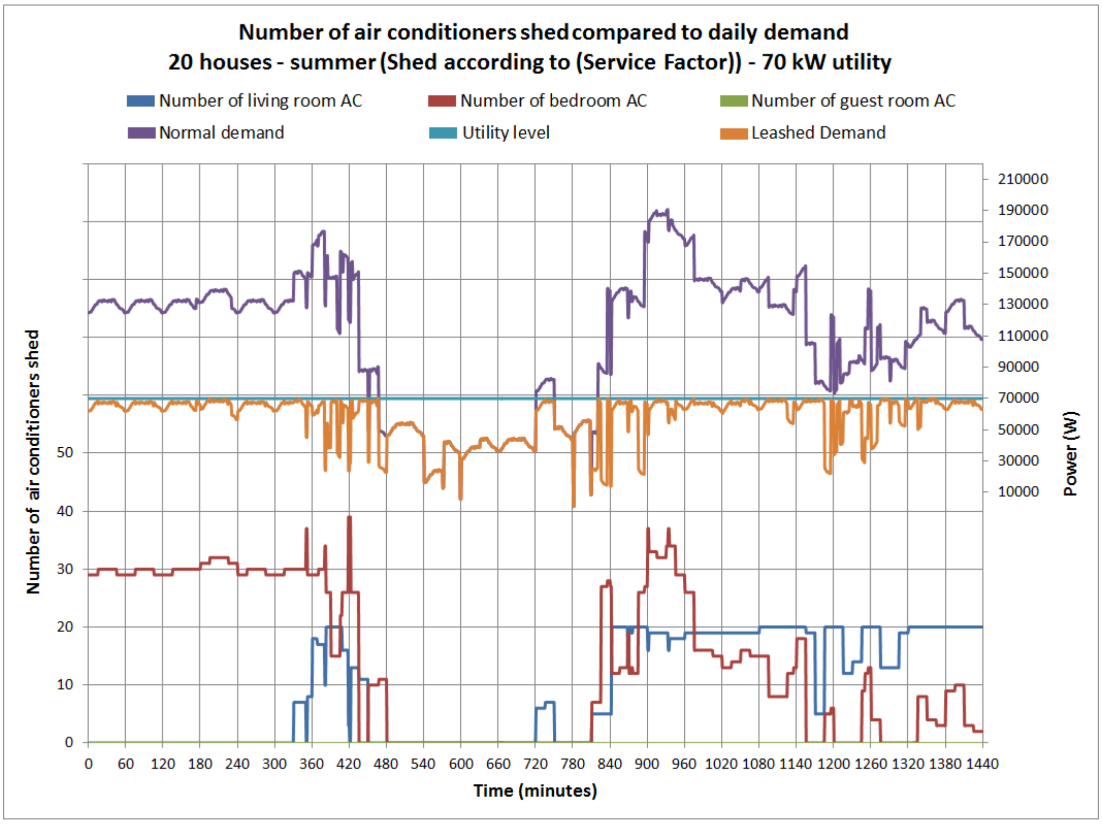


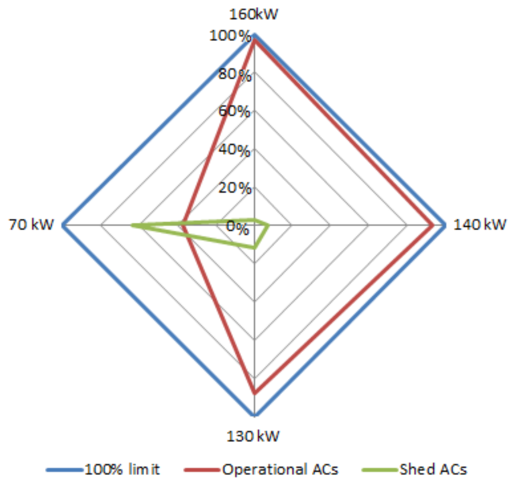
Figure 8.9: A comparison between the original summer demand of 20 houses and managed demands and the number of AC replaced and shed in different rooms during a cyclic blackout HSF-based prevention for a 70 kW utility power level.

Figure 8.10 shows the percentages of living room, bedroom, and total AC shedding time compared to their operation time (measured in minutes); as the utility power level reduces the percentage of shed ACs increases. Figure 8.10(a) shows the overall shedding and operational ACs times and the percentages; Figure 8.10(b) shows the same two quantities for the living room ACs only. Figure 8.10(c) shows them for the bedroom ACs only. The results are summarised in Table 8.1 shows the total number of minutes that the targeted HVACs are in operation, shed, and the related percentages in each of the four utility power levels.

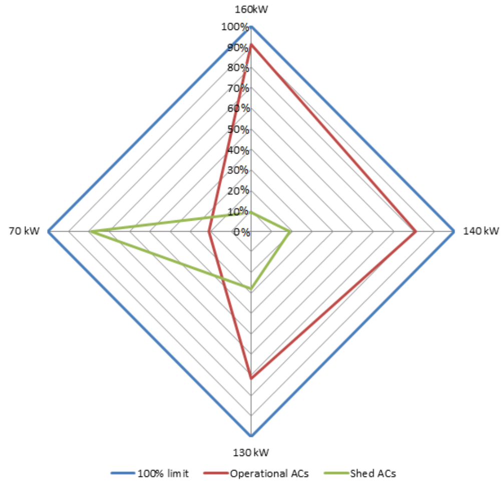
Finally, changing the AC selection criteria from HSF to HTUP has no effect on the result presented, the main impact being on the sequence of the shed ACs.

Table 8.1: A summary of total AC operational time (in minutes) for all rooms for 20 houses.

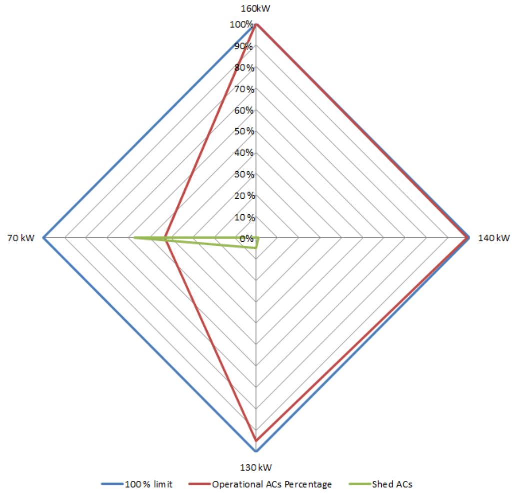
		LR AC			**BR AC**			**GR AC**				**All**	
		Total (min)	**Operational (min)**	**Shed (min)**	**Total (min)**	**Operational (min)**	**Shed (min)**	**Total (min)**	**Operational (min)**	**Shed (min)**	**Total (min)**	**Operational (min)**	**Shed (min)**
Values	**160 kW**	16407	14971	1436	35790	35786	4	680	680	0	52877	51437	1440
	140 kW	16407	13256	3151	35790	35379	411	680	680	0	52877	49315	3562
	130 kW	16407	11822	4585	35790	33986	1804	680	680	0	52877	46488	6389
	70 kW	16407	3406	13001	35790	15567	20223	680	680	0	52877	19653	33224
%	**160 kW**	100	91	9	100	100	0	100	100	0	100	97	3
	140 kW	100	81	19	100	99	1	100	100	0	100	93	7
	130 kW	100	72	28	100	95	5	100	100	0	100	88	12
	70 kW	100	21	79	100	43	57	100	100	0	100	37	63



(a) Overall shed and operated ACs percentages.



(b) Living room AC shed and operation time percentages



(c) Bed room AC shed and operation time percentages

Figure 8.10: The shed and operating time percentages for four utility power levels (160 kW, 140 kW, 130 kW and 70 kW) for 20 houses during the summer season (a) all ACs (b) living room ACs and (c) bed room ACs.

8.3 Dual-Stream Summer Demand Coverage

During spring and autumn – with little or no heating and air conditioning loads - household demand is mainly generated by the residential basic set of appliances (Figure 8.11). The proposed solution follows seasonal dependency in the sense that it changes its way of handling residential demand (Section 4.7.3).

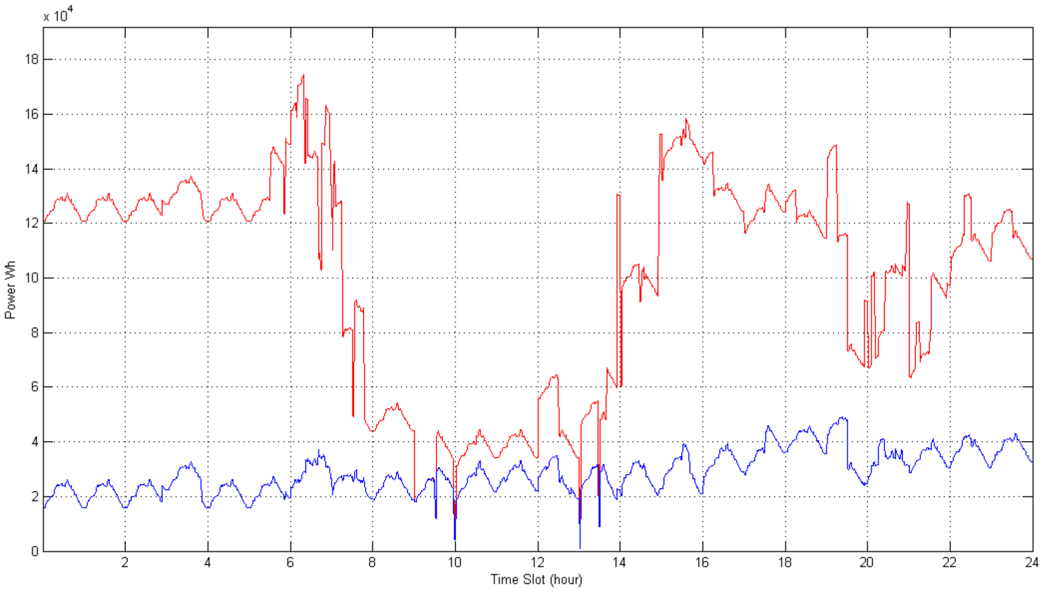


Figure 8.11: Spring demand (blue) and summer demand (red) for 20 houses.

A new application is examined for the case when the utility supply changes from cyclic ON/OFF into a continuous, limited profile throughout the year (Figure 8.12). The 'Dual-Stream' scenario has the advantage of providing a stable limited supply sufficient to sustain residential base load irrespective of air conditioning demand. However, any strategy must be able to manage HVAC demand during the hot season.

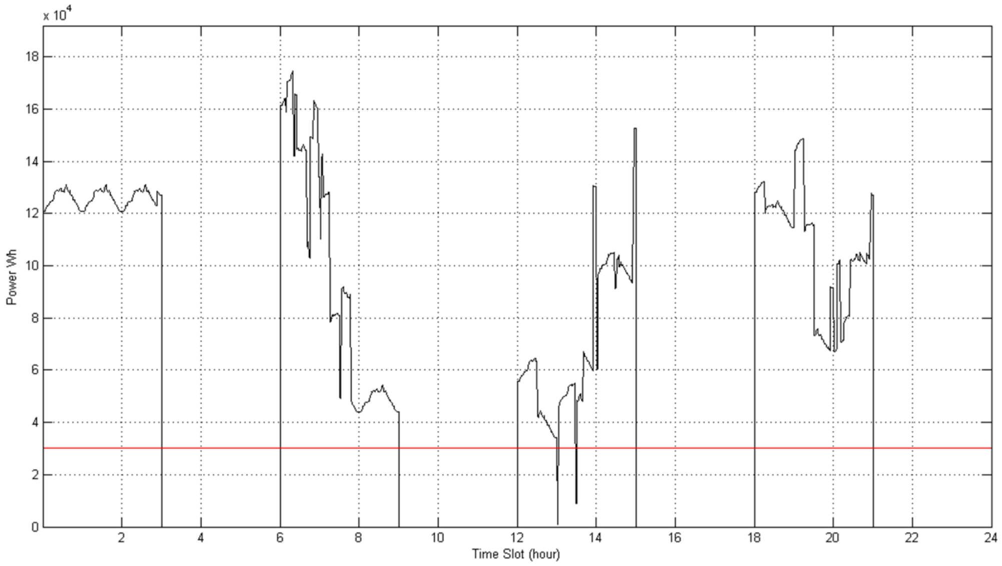


Figure 8.12: The utility supply from cyclic ON/OFF to continuous, limited.

In order to test the system capability to operate efficiently under a continuous limited utility supply, a test case is established in which a range of surplus power levels covering all day are used to support HVAC demand and the overall demand is recorded (Figure 8.13). The 'black' represents surplus power while the 'red' represent the managed HVAC demand supported by that power and the 'blue' represents the total demand, the aggregation of the HVAC demand supported from the surplus power added to the basic set powered from the continuous utility supply.

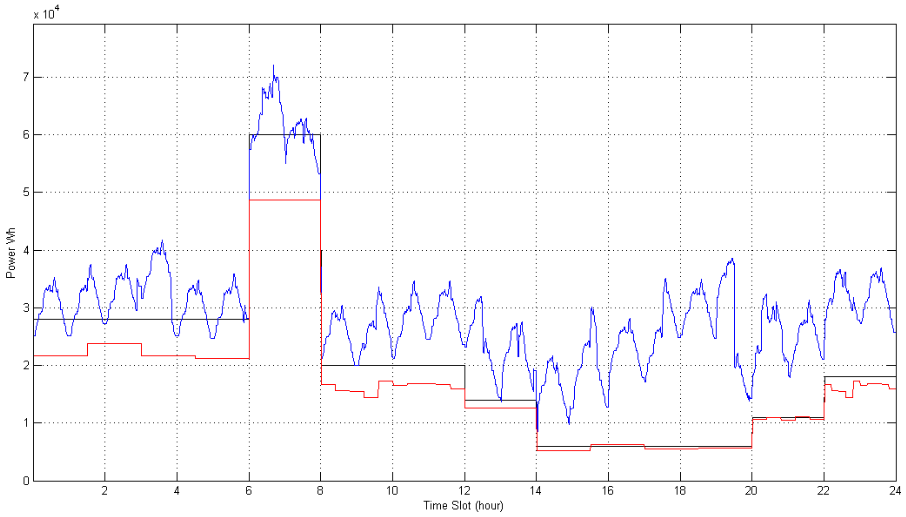


Figure 8.13: Application to the continuous utility basic set supply test case.

The fair share HVAC usage right distribution is used in the test; a different number of household groupings are considered according to the amount of surplus power available (as Chapter 7). It must be noted that such an extension to the system need changes to be made on the proposed hardware system in order to accommodate the incorporation of both the utility and the surplus power.

Applying the same scenario to a typical summer demand is shown in Figure 8.14, showing the normal daily total summer demand of 20 houses (red) to provide a reference for comparison. The snooped power (black), HVAC interlocked demand (purple), and the total demand (blue) which comprises the basic set and HVAC demands added to form the total is also shown. The system manages the demand, and distributes HVAC usage right according to the fair share scheme.

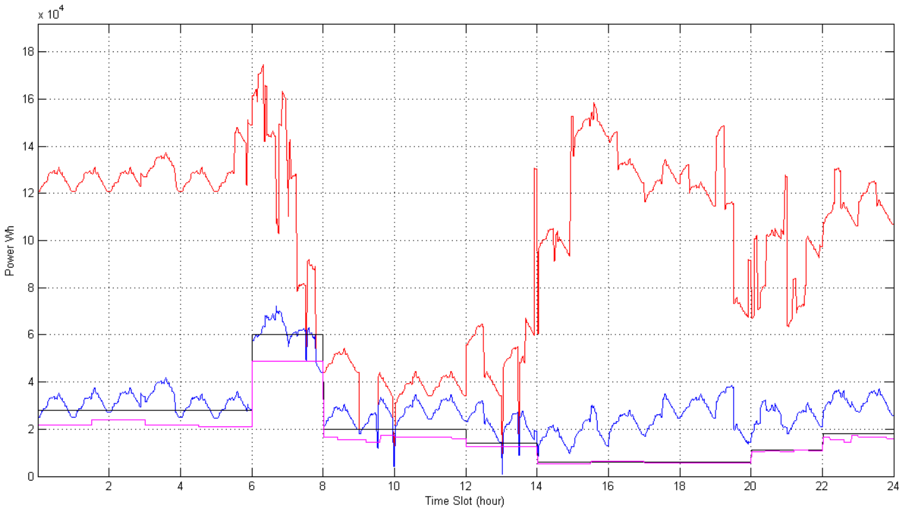


Figure 8.14: The application of PANDA to a continuous utility basic set supply for 20 houses during summer.

Thus far, it has been assumed that the continuous limited utility is allocated equally to all households; however that approach may be open to customer complaint since it does not consider the make-up of the families and their needs e.g. number of individuals in the family. However, meeting the needs on a per household basis adds additional overheads to the management of provisioning supply.

A compromise is required. Segmentation of the available continuous limited power supply equally on a per capita basis and multiplying this base share by the number of individuals in each family yields the family power share, results in an allocated power level per household. The implication of such a scenario is to shift the onus onto to each HAs, tasked with negotiating the level of supply to cover individual power shortages (Chapter 4). Assigning a power share per capita should ensure the supply of sufficient power to small families i.e. a certain minimum supply threshold for all families, regardless their size, must not be exceeded.

8.4 PANDA Limitations

The system suffers from two main limitations; sensitivity to high humidity owing to its dependence on low demand evaporative air cooling techniques and sensitivity to changes in HVAC appliance demand.

8.4.1 High Humidity

Adaptive clustering of interlocked HVAC appliances is at the core of the solution to managing power shortages. However the system's reliance on water evaporation based air cooling makes it sensitive to the humidity level in the air which, if it is high, dilutes their use. In order to ensure the best QoE, humidity should be monitored throughout the residential area and if the humidity level is normal the system performs as described otherwise, areas with high humidity should be allocated sufficient power to operate all ACs on a one per customer basis. This scenario, which could last from few hours to several days, requires a stable, continuous, and sufficient supply of power to support both the basic set and the rationed HVAC, impossible to guarantee from surplus power from standby generation. Humidity compromises the effectiveness of the approach. If securing the required power to drive the air conditioning load is not possible using the available surplus power, then it should be covered, for example, by diverting more utility power for areas subject to high humidity by reducing the utility share of all facilities having sufficient power from standby generation.

Such a change in the HVAC appliance usage patterns has a marked impact on total demand. Figure 8.15 shows a comparison between a normal daily summer demand of 20 houses (red) and the system managed demand under humid weather (blue) during which only ACs are allocated on a one per house basis.

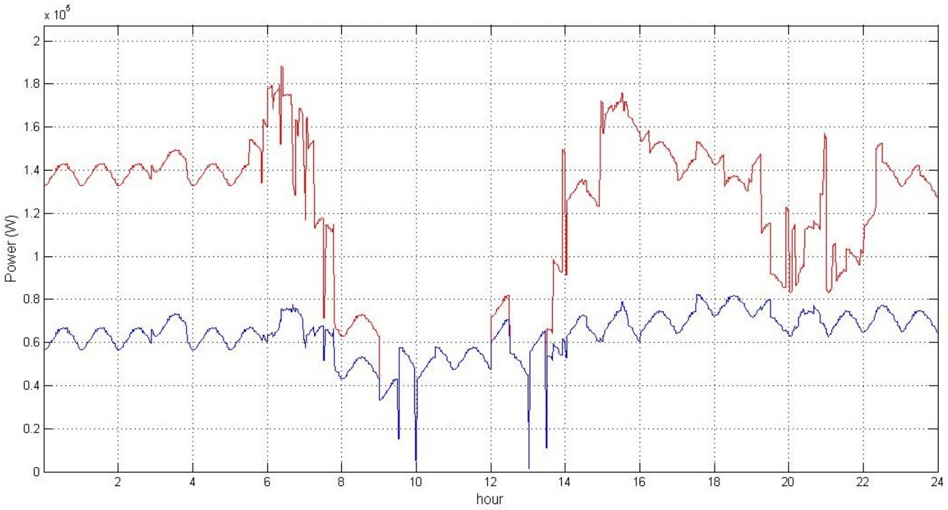


Figure 8.15: Normal (red) and managed (blue) demands under humid weather.

The managed AC-only demand is higher than the typical AC-CO (or CO-MF) demand. Figure 8.16 shows the normal HVAC and single-AC managed demands (HVAC demand only). It is evident that even when allocating the use of one AC, the total managed demand remains a fraction of the normal interlocked HVAC demand.

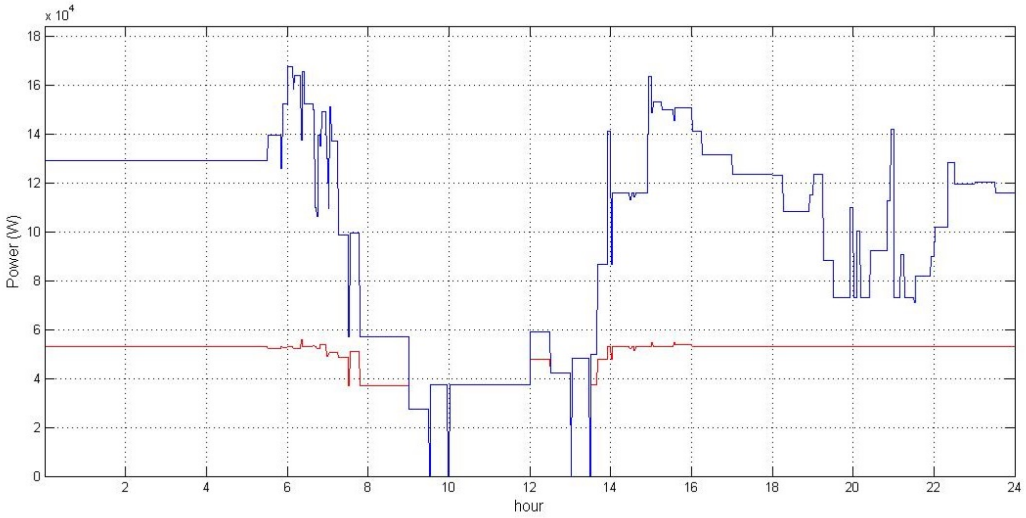


Figure 8.16: Normal and managed AC demand.

For a better insight into the details of this single-AC demand, Figure 8.17 shows its components; the one AC demand (blue), the basic set demand (red), and their total (black), as it can be seen the overall demand is nearly flat.

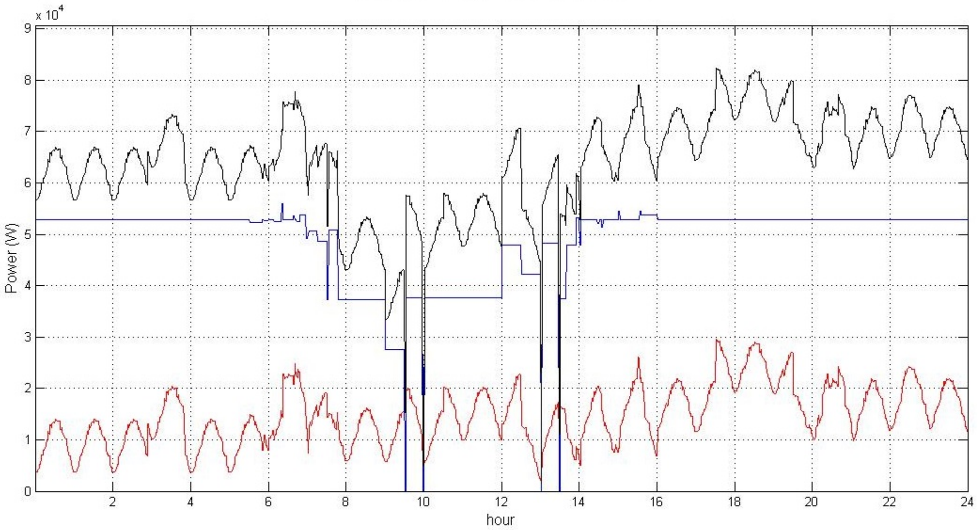


Figure 8.17: The managed summer demand of 20 houses under high humidity.

8.4.2 HVAC Demand Modification

On rare occasions the calculation of HVAC cluster demand is exactly equal or close to the amount of surplus power and any unexpected change in the HVAC demand, due to many factors such as aging, accumulated dust, or even blocking the air flow path of a CO, results in having the calculated cluster demand slightly exceeding the available surplus power. Although these dynamic changes are small, nonetheless a power limit is exceeded for a certain surplus power level. Figure 8.18 shows such a case; for Time Zone 12-14, a surplus power breach occurs in two of the calculated HVAC fair share distribution groups (3rd and 4th). This indicates the need for a certain margin of unallocated surplus power to act as a reserve that manages demand fluctuations.

In general, the main reason that prevents the system from sensing such events is that it gathers HVAC appliance individual demand at the beginning of its operation from values defined at the system's setup phase during its first time installation and continues using these data throughout; any change in demand post initiation of the process goes undetected.

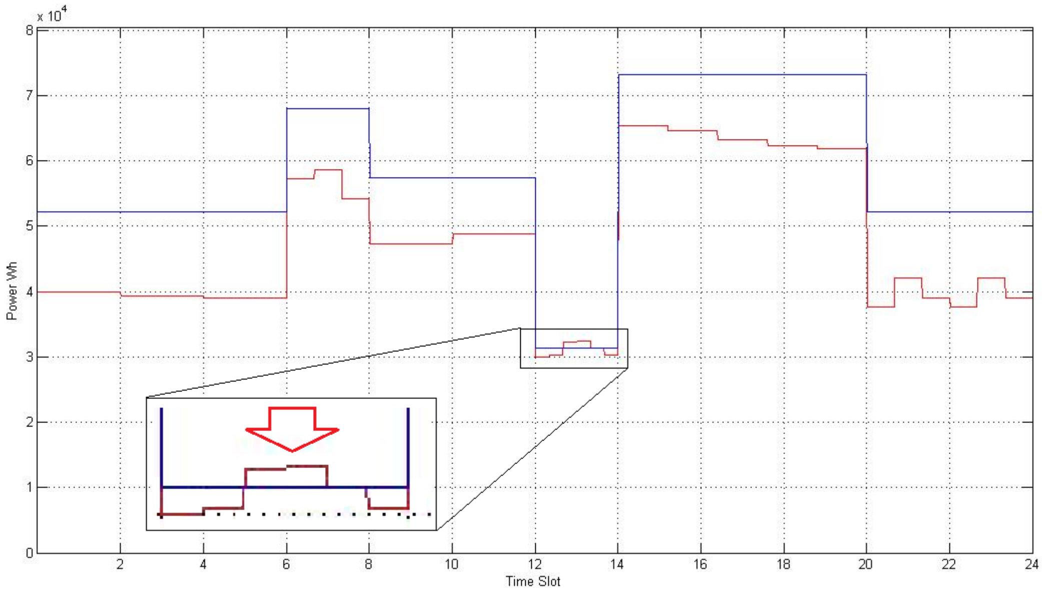


Figure 8.18: HVAC cluster demand exceeding a surplus power level.

There are several solutions to such rare situations such as covering the power deficiency from the unallocated power stored at the system's battery, assuming a worst case scenario when declaring the demand of each HVAC appliance by, for example, adding a certain margin to its true demand, or even keeping a certain percentage of the available power as a reserve.

8.5 Summary

Extensions of the proposed cyclic blackout mitigation strategy are described. The extended mechanisms have been demonstrated the ability of the system to manage the residential demand to fit the available supply which provides a beneficial impact on preventing cycle blackouts, clip peak demand, and smooth overall residential demand. These mechanisms have been developed and tested over a wide range of available utility supply without impacting on its robustness or effectiveness.

In its prevention mode, the strategy is to replace some ACs with their interlocked COs as a measure to reduce rising demand. The number of replaced ACs depends on the desired decrease in demand. Two main criteria are used to select which AC to target during prevention. The first is the HSF in which the average number of people served by a single AC is calculated and those with the lowest HSF are replaced or shed first. In the second, the total number of HVAC usage hours for each room type in each household is calculated and the AC allocated the longest usage periods are replaced or shed first. The approach is also investigated under a dual-stream supply in which the cyclic ON/OFF nature of the utility is replaced with a limited continuous one.

By combining all the approaches mentioned in Chapters 7 and 8 a complete picture of PANDA can be drawn which highlights its merits and reveals its true picture as a complete system that is capable of handling any power shortage, small or large, for any power shortage management application ranging from peak clipping to cyclic blackout mitigation, whether the grid power is limited continuous or unlimited but intermittent. Throughout this wide spectrum of application scenarios PANDA managed to sustain the best possible range of basic household appliances and offering, in a fair way, the best possible air conditioning/cooling to all its beneficiaries.

The proposed approach suffers from two limitations; sensitivity to high ambient humidity and unexpected increase in HVAC appliance demand. In the first case the usage of evaporative air cooling appliances in the proposed demand management strategy results in sensitivity to any severe increases in the ambient humidity compromising the cooling effect. This limitation is managed by supplying the residential area with sufficient continuous utility supply to operate their basic set appliances and one AC during all the humid days and providing the needed power by reducing the utility share of all facilities having standby generators. If this is still insufficient some load shifting in the demand becomes inevitable.

The second limitation was the system sensitivity to changes in the HVAC appliance demand owing to (say) blocking of the air flow path of a CO. This limitation can be solved by different measures such as covering the power deficiency, using stored unallocated and unused surplus power in batteries, adding a margin to each HVAC appliance demand or keeping part of the available power as a reserve.

Chapter Nine
Summary, Conclusions and Future work

9.1 Summary

The power system is one of the most crucial service infrastructures in modern society. Despite being scalable and all related technologies well-established, due to a number of factors, there is still many geographical regions throughout the world plagued by chronic power shortages.

A number of power shortage mitigation measures have been developed ranging from customer awareness campaigns to rotational load shedding used in the severest cases as a last resort which results in cyclic blackouts during which limited power is supplied within a prescribed ON/OFF duty cycle for few hours. Cyclic blackouts are serious problems that are hindering the development of societies around the globe and effective solutions remain much sought after.

The aim of the research is the design and development of a computer-controlled system aimed at mitigating cyclic blackouts especially in hot countries through a practical, transitional solution that can provision power to customers to sustain a set of appliances supporting routine daily- needs and an acceptable level of air conditioning, without the reliance on the installation of new core utility generation capacity. The solution is tested through a case study representative of a severe power shortage scenario and its applicability and effectiveness is proven through simulation.

The case study chosen concerns Iraq, as its core infrastructures have been destroyed in successive wars (1980-2003), resulting in the widespread degradation of the power system. A residential quarter, ‘Kafaat’ in Basra, is the specific area selected as an application field. During the summer months, Iraq produces only half the power needed to cover its peak demand, the majority being consumed by air conditioning systems.

In order to have a deep insight of the different socio-economic factors modulating the current escalating electric demand, a field survey was conducted amongst the population in the selected residential case in order to capture a detailed understanding of family and house structures, type of appliances and their usage pattern and daily routine activities and just as importantly probe, the end user's willingness to collaborate in future solutions. The main findings revealed that firstly Iraqi families in the targeted area have one AC in nearly every room; secondly, the widespread use of affordable COs; thirdly, availability of a wide range of low-cost multiple-size MFs; fourthly, the availability of a substantial level of standby generation distributed throughout the targeted area; and finally, most of these standby generators are underutilised. The survey was reinforced through a series of meetings with managers, engineers, and administrators working in various fields in Basra to secure input and their cooperation.

Informed by the knowledge gained from the field survey, a cyclic blackout mitigation strategy is proposed – referred to as PANDA - based on aggregating all surplus power from underutilised standby generation and its judicious distribution through allocation strategies among households. The allocated power ration is used at the first place to power a basic set of appliances for each family consisting mainly of lights, fans, fridges, and TVs and a single HVAC appliance whose type is determined by the amount of remaining surplus power. All HVAC appliances in the targeted area are clustered, three for each household- an AC, a CO, and an MF – and interlocked so that at any moment only one of HVAC can be operated. The composition of powered appliances within the adaptive interlocked HVAC cluster is determined by the amount of secured power. The ultimate aim of this is to provide each family with active air conditioning during OFF utility periods. Two types of HVAC appliance usage rights strategies are explored; fair share and temperature-triggered. In both cases a certain amount of unallocated power remains (potentially for storage in a dedicated battery for later use or used to enhance the number of operational ACs, and enabling more households to benefit from such power in a fair way).

The proposed power management strategy is essentially a network of co-operating hierarchically organized population of software agents responsible for managing residential house demand and interfacing different generation facilities. These agents are implemented on a system hardware which consists of a group of local controllers one in each household, each hosting a house agent responsible for controlling appliances and sending environmental data to the main controller. Another group of generation interface controllers hosting generation agents are located at each standby generation facility, and finally a centralised controller is located at the local substation hosting the administrative agent responsible for orchestrating all other agents. Each local controller is connected to a rationing smart meter responsible for monitoring the power consumption of each family. All controllers are connected by a suitable implementation-specific communication network.

The system operates by distributing aggregated surplus standby power according to certain criteria. The main challenge is to ensure that every household only consumes their allocated share of power. The rationing smart meter - an enhanced version of the typical smart meter with additional demand limitation capability - is proposed as the central base with which to execute on these functionalities. Each rationing smart meter receives periodically a message specifying the power share for that family, monitors the power consumption of that family and if it exceeds their allocation, the supply is cut off after a suitable warning.

A dedicated software platform – referred to as DDSM-IDEA - was designed to aid in the design and performance analysis of the proposed cyclic blackout mitigation strategy and to display results. The platform has a custom residential demand generator tuned to emulate the used case power consumption using the field study as its root. The platform is designed to provide the user with the maximum possible control over the power management strategy under development.

Simulation results have shown that the system is capable of managing cyclic blackouts by providing continuous yet controlled supply of power to each household during the utility OFF period. Figure 9.1 shows the original utility under 4×2 cyclic blackout (blue) and the power provided by PANDA (green) covering the basic set appliances in addition to a single interlocked HVAC. Evident is the difference between the amount of power needed to maintain an acceptable level of living and the amount of power usually consumed.

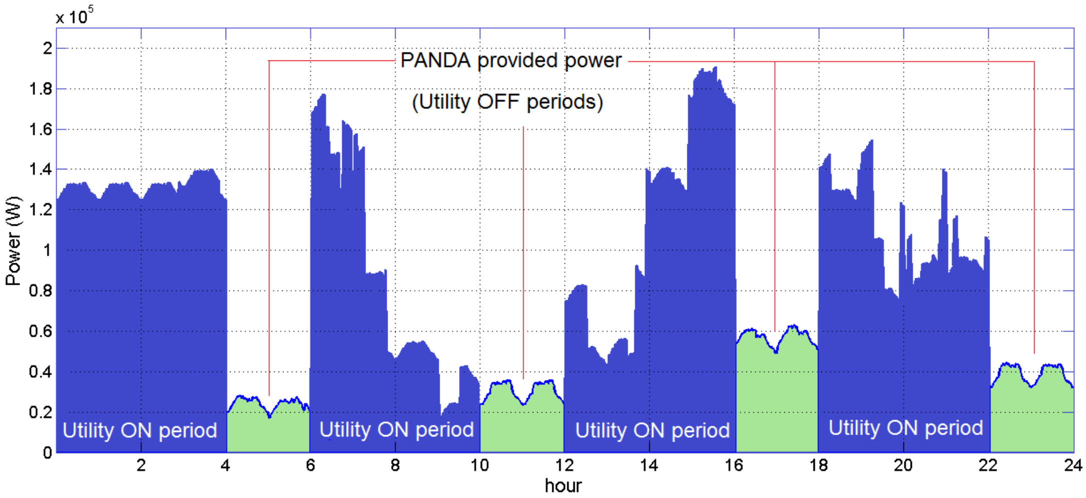


Figure 9.1: PANDA demand coverage

The system has been extended to treat the management of power shortage in normal scenarios i.e. peak clipping and demand smoothing. Results (Figure 9.2) verify the effectiveness of the approach in clipping peak and smoothing overall demand.

Despite its robustness and effectiveness, the system has identifiable limitations. Performance is affected by the level of humidity owing to the reliance for maximum power conservation on evaporative air cooling appliances (COs and MFs). The other factor compromising performance is the potential dynamic changes in HVAC appliance demand owing to several factors. Solutions to both these issues have been described.

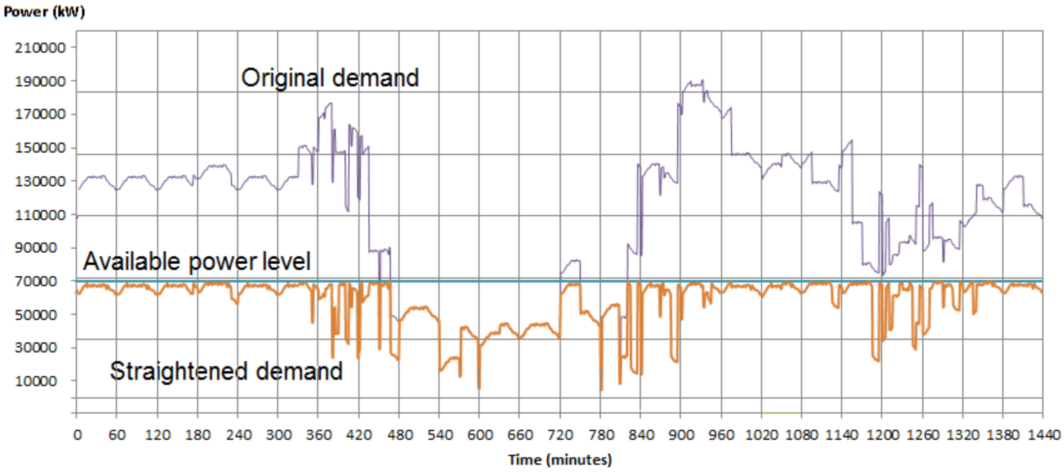


Figure 9.2: PANDA's peak clipping and demand straightening capabilities

9.2 Conclusions

Current technological advances have yielded a growing power demand unable to be satisfied in many countries resulting in severe power shortages. Establishing additional core generation capacity coupled with demand management and reinforced with the full utilisation of all available standby generators integrated within a balanced SDM mechanism is the key to successful future demand coverage.

Distributed standby generation facilities are much under-estimated generation assets that can play an important role in solutions that cover power shortages. The aggregation of surplus power creates a flow of power providing a valuable, albeit limited service to residential areas during blackouts. The allocation is a significant improvement to chronic power shortages, providing an increased QoE and an improved level of comfort to customers. Rationing smart meters are a core implementation infrastructure to execute monitoring, control and allocation operations and tasks.

PANDA was applied successfully to an Iraqi use case due to the availability and cheap prices of certain energy sources e.g. natural gas used primarily for cooking and heating purposes. In other countries and scenarios where electricity is the main source of energy for cooking and heating, a more significant level of standby generation is required to meet what is a sizeable component of overall demand. A more detailed study that manages cooking and heating as part of the solution should be conducted and suitable measure proposed.

Although agents are well-suited for distributed problems, their integration with a certain degree of central control enhances results. A careful balance should be established on distributing power management tasks among agents so as not to overload with processor-intensive duties which could degrade their performance.

In situations where there is scarce statistical data concerning electricity demand, demand generators based on individual daily activities and appliance usage patterns can be an acceptable substitute for accurate load models. The current version of the abstract demand generator does not consider the use of hair dryers and irons as both represent high power consumption appliances. Dedicated DSM such as load shifting with or without the use of the stored energy integrated into the proposed hardware architecture can be used to cover this high demand. Dedicated well-designed software platforms and suitable test beds devoted to the execution of power management strategies and proof-of-concept validation are valuable aids to researchers.

The proposed solution is far from complete; several issues remain unresolved such as developing a more practical fair power distribution strategy, the impact of LVDN characteristics, line rating and the effect of current flow directions owing to changes of participating generators. The response time of the system as a function of different scenarios and its effect on performance must be quantified. Moreover, selection of the appropriate communication network and its impact on the performance of the solution remains outstanding.

9.3 Future Work

The research has raised a range of future challenges.

- conducting detailed customer surveys, on a frequent basis, that provide the needed foundation to validate any future demand modelling.
- creating a library of types of agents and different types of power management strategies inside the DDSM-IDEA platform to speed up development operations
- consideration of the mutual interaction between individual family members
- the impact of weather on family activities and usage patterns
- discriminating demand during weekends from normal weekdays
- determining the feasibility and benefits of converting the current 'hardwired' agent architecture into a standard complying with the Foundation for Intelligent Physical Agents (FIPA) standards [164]. This includes studying the effects and benefits of such standardisation on overall system performance.
- building a test bed for evaluating developed strategies and providing a proof-of-concept mechanism following their verification on the DDSM-IDEA platform. This should include generators, programmable controllers, one or more type of wired/wireless communication networks, main control computer and security apparatus, all the necessary software such as PC-based monitoring and control packages that monitor all test bed hardware and software entities and log all data and packet transfers within the system.
- adding more agent activities monitoring, evaluation, and analysis capabilities integrated into the DDSM-IDEA platform in order to provide direct-on-GUI agent related results. In the current version agent-related activities data are extracted through different data structures and activity log files, plotted separately.

- study of the LVDN and its parameters affected by connecting a variable number of ACs, their switching ON sequences, and generated inrush current
- determining a suitable symbolic agent programming language and designing an interpreter/compiler for implementation in the DDSM-IDEA platform. A symbolic agent programming language means that normal agent operations are described as flowchart-like symbols fed to the agent language interpreter to produce the final agent control code. "Business Process Modelling Notation" (BPMN) symbols are graphical representations of various business processes used in a typical business process model, can also be used for describing various agent activities as seen in Figure 9.4 and Figure 9.3 displaying prototype house AA and HA designs in this manner.

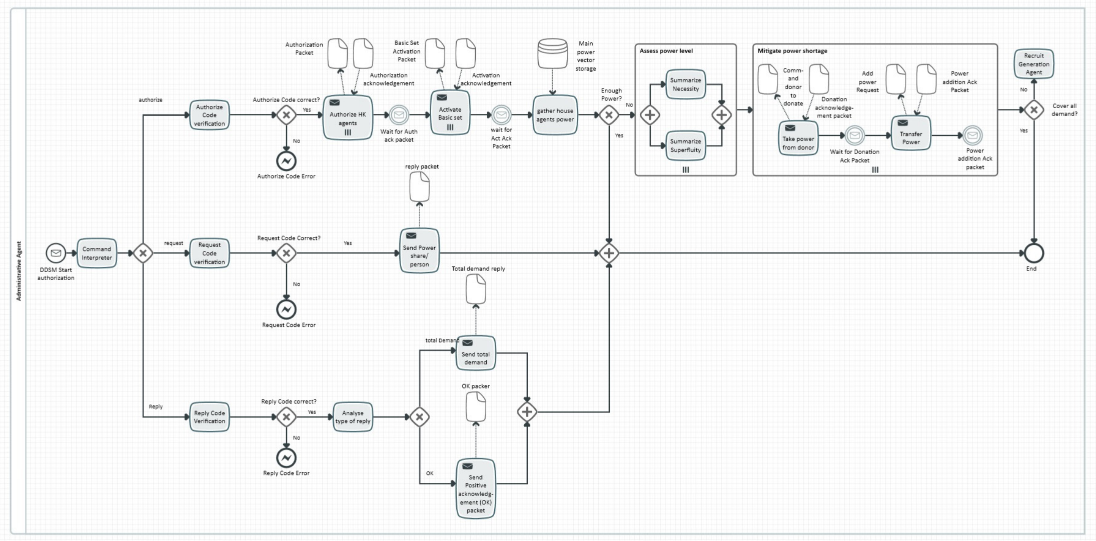


Figure 9.3: BPMN description of an administrative agent.

- adding human-like inter-agent relationships (such as friendship and family) to mimic real-life situations. These kind of relationships are important in inter-agent surplus power negotiations since they enable people-based prioritisation schemes to be implemented.
- design, implementation and test of the rationing smart meter in order to verify its operation

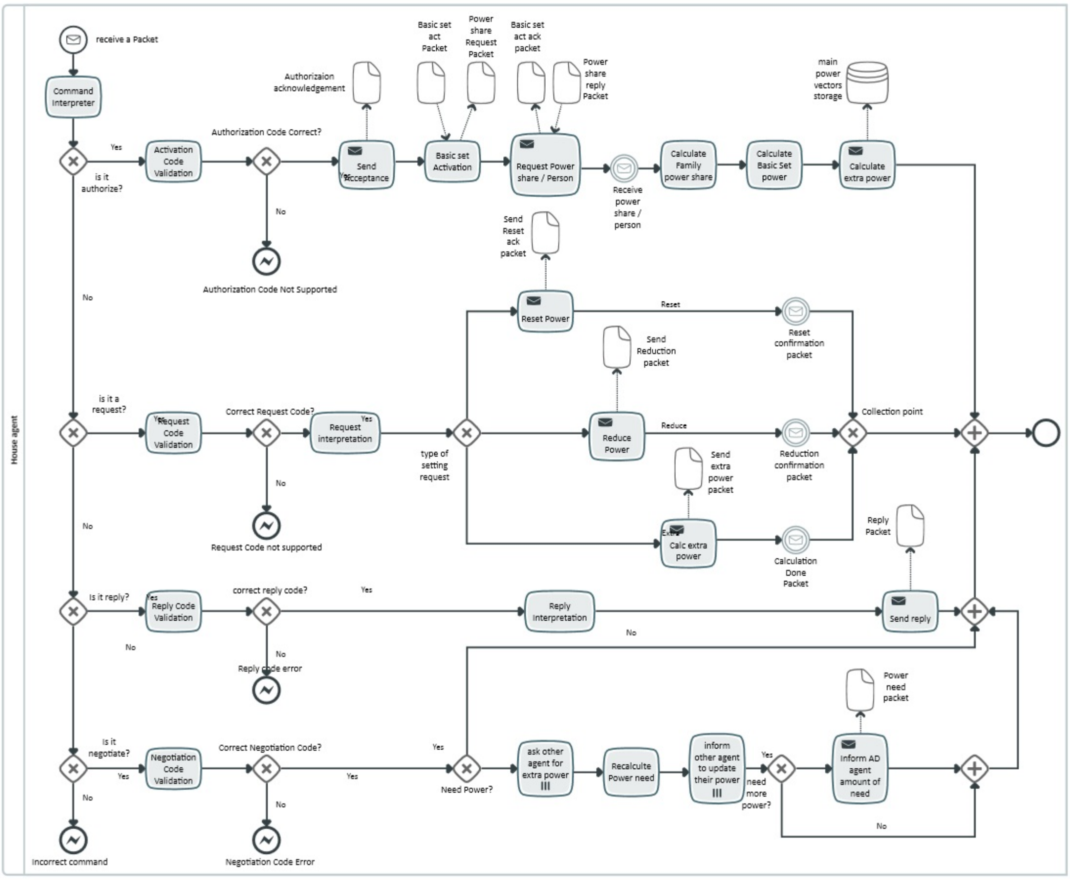


Figure 9.4: BPMN description of a house agent.

- integrating the local controller within the rationing smart meter to yield a single unit
- adding bi-directional request-message capabilities to the rationing smart meter so that it can send customer requests and receive alarms, network status and expected demand limits from the utility. In this way the rationing smart meter works as an interactive bulletin board for utility-customer interactions in turn making it an important awareness campaign tool
- addition of an automatic capability to rationing smart meter to redefine the basic set of appliances so that in emergency cases, customers are provided with a minimum amount of power simply to operate lights and fans which is supplied by a single local generator.
- enabling the rationing smart meter to have ON/OFF control over individual appliances

- documenting various power generation, transmission, distribution and consumption data (residential, commercial, and industrial)
- There are other issues associated with the implementation of the concepts that must be addressed. The impact of the addition of new generation assets or removal of outdated infrastructure must be determined. For instance, on the installation of a new generator necessitates a system update to recognize the new generator along with the necessary modification to the main power stream such as connection devices, phase measurement units, protection instruments, and communication links. Removal of a generator set will need similar measures but with the aim of excluding the removed generator set from the recruited pool.
- Another factor that must be taken into consideration is the effect of scalability in terms of the number of houses in the targeted residential quarter. A recent study aimed at improving PANDA's fair distribution strategy by excluding empty houses from the power allocation process has pinpointed the severe effect of the extent of the residential quarter, the number of houses being a prime factor. The study showed that a certain number of houses can result in considerable levels of unallocated power, which, in the current configuration, is assumed to be stored. Further research is needed to provide better fair share air conditioning distribution strategies such as using the unallocated power to enhance the HVAC distribution and allocating this surplus power to all households sequentially or considering house occupancy in the HVAC distribution process.
- There are several power engineering aspects that would require to be considered in an actual implementation of this system. These include:
    - safety and operability issues associated with islanded operation, reconnection of islands and consideration of synchronising;
    - earthing of the system in various stags;
    - how the system would be protected against short circuits, unbalanced and overloaded operation;

    - the capabilities of conductors to carry power in various states of system configuration;
    - reactive power flows and management, voltage drops and other power quality issues
- PANDA in its current configuration depends heavily on government-owned standby gensets whose operational and fuel cost is paid by the government. Adding new commercially or privately owned gensets raises the question about who is responsible for covering their operational and fuel cost. One possible scenario is to let the people pay these fees on a per kW bases. More studies are needed to examine issues such as apply different tariffs (time of use, critical peak price, and block tariffs) to buy power. Other possible issues that need more study is payment during limited utility supply scheme suggested in chapter 8.
- Due to the various requirements of PANDA, operating such system, installing its controllers and connecting them, measuring its different distribution network parameters, upgrading its strategies, raising the efficiency of the used appliances … etc. among other things are crucial factors that must be taken into consideration. A thorough and detailed training must precede its application for all its installation, operating, and development staff.
- In order to assess the impact of applying this system the temperature and humidity of every house should be measured before and after the application of the system to record its success degree. This should take into consideration the power ON and OFF periods of the cyclic blackout with and without PANDA intervention. This will not be a replacement but a an addition to the temperature and humidity measurement carried out by PANDA during its temperature-based HVAC distribution.

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Appendix (A) Glossary

Advanced Metering Infrastructure (AMI): AMI is defined as the communications hardware and associated system and data management software that creates a network between advanced meters and utility business systems and which allows collection and distribution of information to customers and other parties such as competitive retail providers, in addition to providing it to the utility itself.

Ancillary Services: Those services necessary to support the transmission of electric power from seller to purchaser, given the obligations of control areas and transmitting utilities within those control areas, to maintain reliable operations of the interconnected transmission system. Ancillary services supplied with generation include load following, reactive power-voltage regulation, system protective services, loss compensation service, system control, load dispatch services, and energy imbalance services.

Ancillary Service Market Programs: Demand response programs in which customers bid load curtailments in ISO/RTO markets as operating reserves. If their bids are accepted, they are paid the market price for committing to be on standby. If their load curtailments are needed, they are called by the ISO/RTO, and may be paid the spot market energy price.

Critical Peak Pricing (CPP): CPP rates are a hybrid of the TOU and RTP design. The basic rate structure is TOU. However, provision is made for replacing the normal peak price with a much higher CPP event price under specified trigger conditions (e.g., when system reliability is compromised or supply prices are very high).

Demand: Represents the requirements of a customer or area at a particular moment in time. Typically calculated as the average requirement over a period of several minutes to an hour, and thus usually expressed in kilowatts or megawatts rather than kilowatt-hours or megawatt-hours. Demand and load are used interchangeably when referring to energy requirements for a given customer or area.

Demand Bidding/Buyback (DB): A demand response program where customers or curtailment service providers offer bids to curtail based on wholesale electricity market prices or an equivalent. Mainly offered to large customers (e.g., one MW and over), but small customer demand response load can be aggregated by curtailment service providers and bid into the demand bidding program sponsor.

Demand Response (DR): The planning, implementation, and monitoring of activities designed to encourage customers to modify patterns of electricity usage, including the timing and level of electricity demand. Demand response covers the complete range of load-shape objectives and customer objectives, including strategic conservation, time-based rates, peak load reduction, as well as customer management of energy bills.

Demand Response Event: A period of time identified by the demand response program sponsor when it is seeking reduced energy consumption and/or load from customers participating in the program. Depending on the type of program and event (economic or emergency), customers are expected to respond or decide whether to respond to the call for reduced load and energy usage. The program sponsor generally will notify the customer of the demand response event before the event begins, and when the event ends. Generally each event is a certain number of hours, and the program sponsors are limited to a maximum number of events per year.

Demand Response Load: The load reduction that results from demand response activities.

Direct Load Control (DLC): A demand response activity by which the program operator remotely shuts down or cycles a customer’s electrical equipment (e.g. air conditioner, water heater) on short notice. Direct load control programs are primarily offered to residential or small commercial customers.

Duration of Event: The length of an Emergency or Economic Demand Response Event in hours.

Edison Electric Institute (EEI): The trade association for the investor-owned utility companies.

Electric Power: The rate at which electric energy is transferred. Electric power is measured by capacity and is commonly expressed in megawatts (MW).

Electric Power Research Institute (EPRI): An independent, non-profit energy and environmental research organization which brings together members, participants, and the Institute's scientists and engineers to work collaboratively on solutions to electric power issues.

Electric Utility: A corporation, person, agency, authority, or other legal entity or instrumentality aligned with distribution facilities for delivery of electric energy for use primarily by the public. Included are investor-owned electric utilities, municipal and state utilities, federal electric utilities, and rural electric cooperatives. A few entities that are tariff based and affiliated with companies that own distribution facilities are also included.

Electricity: A form of energy characterized by the presence and motion of elementary charged particles generated by friction, induction, or chemical change.

Emergency Demand Response Event: A demand response event called by the program sponsor in response to an emergency of the delivery system of the demand response sponsor or of another entity such as a utility or ISO.

Emergency Demand Response Program (EDRP): A demand response program that provides incentive payments to customers for load reductions during periods when reserve shortfalls arise.

Energy: The capacity for doing work as measured by the capability of doing work (potential energy) or the conversion of this capability to motion (kinetic energy). Energy has several forms, some of which are easily convertible and can be changed to another form useful for work. Most of the world's convertible energy comes from fossil fuels that are burned to produce heat that is then used as a transfer medium to mechanical or other means in order to accomplish tasks. Electrical energy is usually measured in kilowatt-hours.

Energy Efficiency (EE): Refers to programs that are aimed at reducing the energy used by specific end-use devices and systems, typically without affecting the services provided. These programs reduce overall electricity consumption (reported in megawatt-hours), often, but not always, without explicit consideration for the timing of program-induced savings. Such savings are generally achieved by substituting technologically more advanced equipment to produce the same level of end-use services (e.g. lighting, heating, motor drive) with less electricity. Examples include energy saving appliances and lighting programs, high-efficiency heating, ventilating and air conditioning (HVAC) systems or control modifications, efficient building design, advanced electric motor drives, and heat recovery systems.

Framework: is a suite of inter-related libraries and modules which were separated into either general or specific categories. The code under development is inserted in the framework that provides the needed resources to the inserted code which runs under the framework's control.

Independent system operator (ISO): An organization that has been granted the authority to operate, in a non-discriminatory manner, the transmission assets of the participating transmission owners in a fixed geographic area. ISOs often run organized markets for spot electricity.

Interlock: A device or mechanism for connecting or coordinating the function of different components

Library (software): is a collection of code relating to a specific task.

Load (Electric): The amount of electric power delivered or required at any specific point or points on a system. The requirement originates at the energy-consuming equipment of the consumers.

Load acting as a Resource (LaaR): An interruptible program operated by ERCOT in which customers may qualify to provide operating reserves.

Load-serving entity (LSE): Any entity, including a load aggregator or power marketer, that serves end-users within a control area and has been granted the authority or has an obligation pursuant to state or local law, regulation, or franchise to sell electric energy to end-users located within the control area.

North American Electric Reliability Council (NERC): The organization certified by the Commission as the reliability organization for the nation's bulk power grid. NERC consists of eight Regional Reliability Councils in the lower 48 states. The members of these Councils are from all segments of the electricity supply industry -

investor-owned, federal, rural electric cooperative, state/municipal, and provincial utilities, independent power producers, and power marketers.

Outage Management: The response of an electric utility to an outage affecting the ultimate customers of the electric service. The utility may use the AMI network to detect outages, verify outages, map the extent of an outage, or verify the service has been restored after repairs have been made.

Peak Demand: The maximum load during a specified period of time.

Power line communications (PLC): is providing broadband data communications on conductors already used for electric power transmission using a modular signal. Power line communications (PLC) provides broadband data communications on conductors already used for electric power transmission using a modular signal.

Power Marketers: Business entities, including energy service providers, that are engaged in buying and selling electricity, but do not own generating or transmission facilities. Power marketers and energy service providers, as opposed to brokers, take ownership of the electricity and are involved in interstate trade. Power marketers file with the Federal Energy Regulatory Commission (FERC) for status as a power marketer. Energy service providers may not register with FERC but may register with the states if they undertake only retail transactions.

Premise Device/Load Control Interface or Capability: The ability of the AMI network to communicate directly with a device located on the premises of the ultimate customer, which may or may not be owned by the utility. These might include a programmable communicating thermostat or a load control switch.

Price Responsive Demand Response: All demand response programs that include the use of time-based rates to encourage retail customers to reduce demands when prices are relatively high. These demand response programs may also include the use of automated responses. Customers may or may not have the option of overriding the automatic response to the high prices.

Public Utility: An enterprise providing essential public services, such as electric, gas, telephone, water, and sewer under legally established monopoly conditions.

Publicly Owned Electric Utility: A class of ownership found in the electric power industry. This group includes those utilities operated by municipalities, political subdivisions, and state and federal power agencies (such as BPA or TVA).

Real Time Pricing (RTP): A retail rate in which the price for electricity typically fluctuates hourly reflecting changes in the wholesale price of electricity. RTP prices are typically known to customers on a day-ahead or hour-ahead basis.

Regional transmission organization (RTO): An organization with a role similar to that of an independent system operator but covering a larger geographical scale and involving both the operation and planning of a transmission system. RTOs often run organized markets for spot electricity.

Remote Connect/Disconnect: The ability to physically turn on or turn off power to a particular billing or revenue meter without a site visit to the meter location.

Residential: The energy-consuming sector that consists of living quarters for private households. Common uses of energy associated with this sector include space heating, water heating, air conditioning, lighting, refrigeration, cooking, and running a variety of other appliances. The residential sector excludes institutional living quarters. This sector may exclude deliveries or sales to apartment buildings or homes on military bases (these buildings or homes may be included in the commercial sector).

Retail: Sales covering electrical energy supplied for residential, commercial, and industrial end-use purposes. Other small classes, such as agriculture and street lighting, also are included in this category.

Software Development Kit (SDK): is a collection of tools to assist the programmer to create and deploy code/content which is very specifically targeted to either run on a very particular platform or in a very particular manner.

System (Electric): Physically connected generation, transmission, and distribution facilities operated as an integrated unit under one centralized manager or operations supervisor.

Time-Based Rate (TBR): A retail rate in which customers are charged different prices for different times during the day. Examples are time-of-use (TOU) rates, real time pricing (RTP), hourly pricing, and critical peak pricing (CPP).

Time-of-use (TOU) Rate: A rate with different unit prices for usage during different blocks of time, usually defined for a 24 hour day. TOU rates reflect the average cost of generating and delivering power during those time periods. Daily pricing blocks might include an on-peak, partial-peak, and off-peak price for non-holiday weekdays, with the on-peak price as the highest price, and the off-peak price as the lowest price.

Toolkit: is a focussed library, with a defined and specific purpose.

Transmission System (Electric): An interconnected group of electric transmission lines and associated equipment for moving or transferring electric energy in bulk between points of supply and points at which it is transformed for delivery over the distribution system lines to consumers.

Appendix (B) DLC Infrastructure

A comprehensive infrastructure is required to implement a successful DR strategy comprising load control such as load control switches and intelligent thermostats. A generic DLC system has [70] [243], [244], [119]:

- one or more main controllers depending on the size of the system and whether it is controlled in a centralised or distributed fashion. This could range from a single PC to a full SCADA system depending on the size and complexity of the power system and its configuration.
- a communication system that connects all the components of the power system in both the supply and demand sides and used to transfer control commands, metering readings and status information. Several technologies are used to connect various parts of the supply-demand infrastructure such as normal telephones, pagers, fax, radio signals and the Internet.
- a monitoring system comprising an Advanced Metering Infrastructure (AMI) for measuring current demand and Energy Management Systems (EMS) to optimise the demand according to the applied control strategy
- local controllers and switches including various types of load control switches, intelligent thermostats, and any other type of devices that can be used for load control.

Figure B.1 shows the structure of such system.

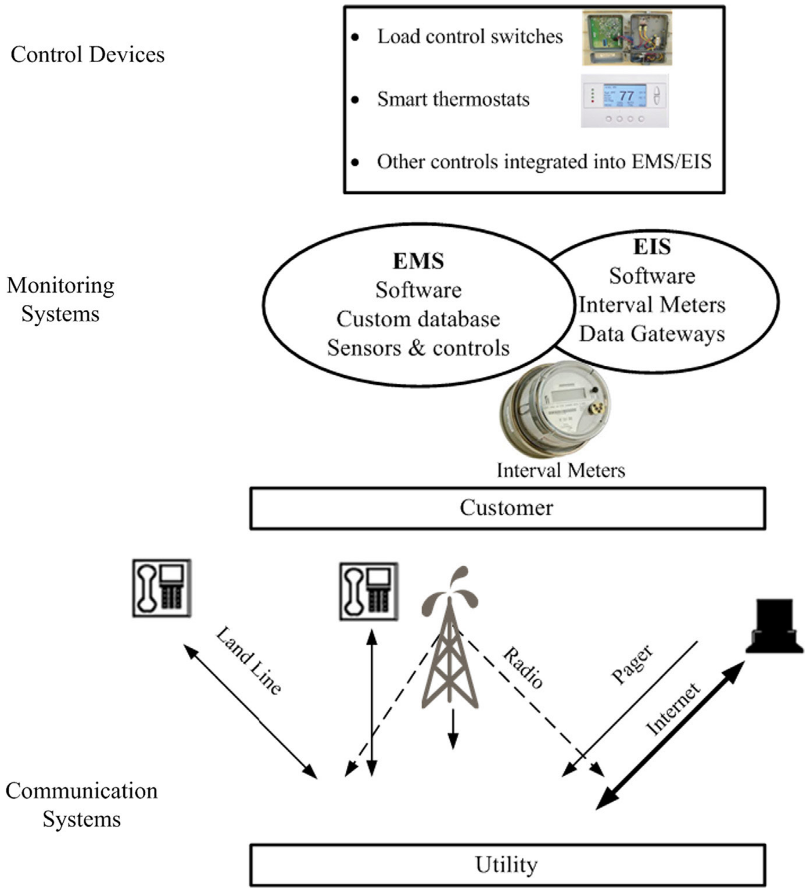


Figure B.1: Direct Load Control infrastructure [245].

Appendix (C) DLC Scenarios

DLC is initiated by a contract between the customer and the utility providing authorisation to manage the former’s demand during peak demand periods and power supply shortages. The goal is to reduce the load during such occasions to avoid expensive power buying operations for a limited number of hours per year. Table C.1 illustrates the elements of a typical practical DLC scenario, offered by Wisconsin Public Services (WPS).

Table C.1: A typical Direct Load Control scenarios [246].

	Scenario 1: Summer 50% cycling	**Scenario 2: Summer 100% load shedding**	**Scenario 3: Year-Round 100% Load Shed**
Equipment	Air conditioning	Air conditioners, decorative fountains, irrigation systems or other equipment operated only in the summer	Lighting, water heating, motors or pumps or other ones that are operated year round
Cycle time	Shut off 15 every 30 minutes	8 hours/day	
Hours off per calendar year	<= 100	<=50	<= 100
Bill credit ($US)	$ 6.5 /kW/month June-September		$ 4.35 /kW/month All year

Appendix (D) The Cuban Energy Efficiency Campaign

One of the successful energy efficiency campaigns is the Cuban experience and it is described in more detail due to its noteworthy achievements. The Cuban energy efficiency campaign (known as the CFL and appliance replacement campaign) replaced kerosene and incandescent lamps with electric cookers and CFLs and old non-efficient appliances with new ones. The aim of the campaign was to reduce the overall power demand whilst introducing a health and environmental enhancement. CFL replacement alone achieved a reduction of 354 million kWh, representing 3%-4% reduction in the overall Cuban electricity total demand. The Cuban government is currently planning to replace CFL lamps with even more energy efficient and longer life LEDs.

The appliance replacement campaign included replacing old with new more efficient refrigerators. A refrigerator consumes an average of 700-900 kWh/year/household, nearly 42%-54% of the total annual consumption of a typical Cuban household. During this campaign 2.5M old refrigerators were replaced, 96% of the total refrigerators in Cuba yielding a 450 kWh/refrigerator/year reduction in demand. The campaign also included replacing inefficient fans, air conditioners, TVs, and water pumps. Table D.1 shows the detailed numbers of replaced lamps and appliance.

The appliance replacement campaign also included the replacement of old kerosene and gas cookers with electric ones for health and environmental enhancement and although the major environmental goals were achieved the replacement process has an associated overhead by increasing the overall power demand by 33%. The campaign was skilfully crafted, overlooked nothing, and paid careful attention to all supporting measures; for example there was a huge administrative and supportive ‘behind-the-scene’ effort in importing, storing, distributing, installing, repairing, and replacing as well as educating people is also impressive [247].

Table D.1: The Cuban lamp and appliance replacement scheme [248].

Device or Appliance	Total Number	Replacement %	Replacement Goal	Phase 2 Replacement	Disadvantages	Cost
CFL lights	9,470,710	100%	Electric power demand reduction	LED lights	None	Free
Refrigerators	2,550,997	96%		None	Families should pay the cost of appliances	Billed
Fans	1,043,709	100%				
TVs	230,504	22%				
Air conditioners	265,505	88%				
Water pump	267,568	100%				
Immersing water heater	3,037,673	94%	Health and environmental enhancement + GHG reduction		33% increase in total demand between 2004 and 2008	
Cooking pots	3,595,139	103%				
Gas Cooker	3,242,591	99%				
Pressure cooking pot	3,222,872	92%				
Rice cooker	3,557,043	102%				

Appendix (E) DSM Terminology

Demand Side Management plays an important role in modern supply-demand balance and matching. Since its introduction, six DSM operations have been identified as core [249]:

- **Peak Clipping:** a major and direct operation which manages the demand peak using various techniques such as load shifting, direct load control, e.g. HVAC demand reduction during peak hours through appropriate thermostatic control, or targeted pricing.
- **Load Shifting:** the demand is not curtailed but rescheduled to another time during the day, usually outside peak times e.g. storage water and space heating.
- **Valley Lifting:** the peak is not modulated but rather the off peak zones in the targeted demand are enhanced i.e. more consumption is executed during these periods of the day e.g. operating a water pump during the off peak times to fill a swimming pool.
- **Strategic Conservation:** the target is the reduction of the demand profile, i.e. an overall reduction in energy consumption, which is usually executed through changes in the energy consumption pattern e.g. weather-related demand changes and utilisation of higher efficiency appliances.
- **Strategic Load Growth:** the overall demand is increased throughout the day in an attempt to increase energy selling, for example as a result of replacing a certain fuel with electricity. The operation is the opposite of strategic conservation. Examples of such operations are HVAC usage pattern moderation in the summer and winter periods and the introduction of new technologies such as electric vehicles.

- **Flexible Load Shape:** the overall demand curve is nominated for reshaping such as in reliability-related issues. The change can be negotiated with customers to secure their permission to participate in such operation.

Inconsistencies in DSM terminology prompted the International Council on Large Electric Systems (CIGRE) to introduce the term Demand Side Integration (DSI) which refers to all activities focused on advancing the efficiency of electricity utilisation including demand response and energy efficiency, thus DSI includes all demand-side activities [65] and is more representative of the modern restructured power industry.

To clarify the major differences between DSM and DSI terminology, [250] has compared the traditional six DSM operations with counterparts in the new DSI (Figure E.1). “Load conservation” is referred to as “Energy Efficiency (EE)”, “Load Flexibility” as “Dynamic Energy Management” and “Load Management (LM)” as “Demand Response (DR)”. It is worth noting that DR is not restricted to traditional DSM operations as new DSM operations related to energy pricing fall under the DR umbrella. For the sake of clarity and consistency the term DSM is used in this research including the new DSI operations.

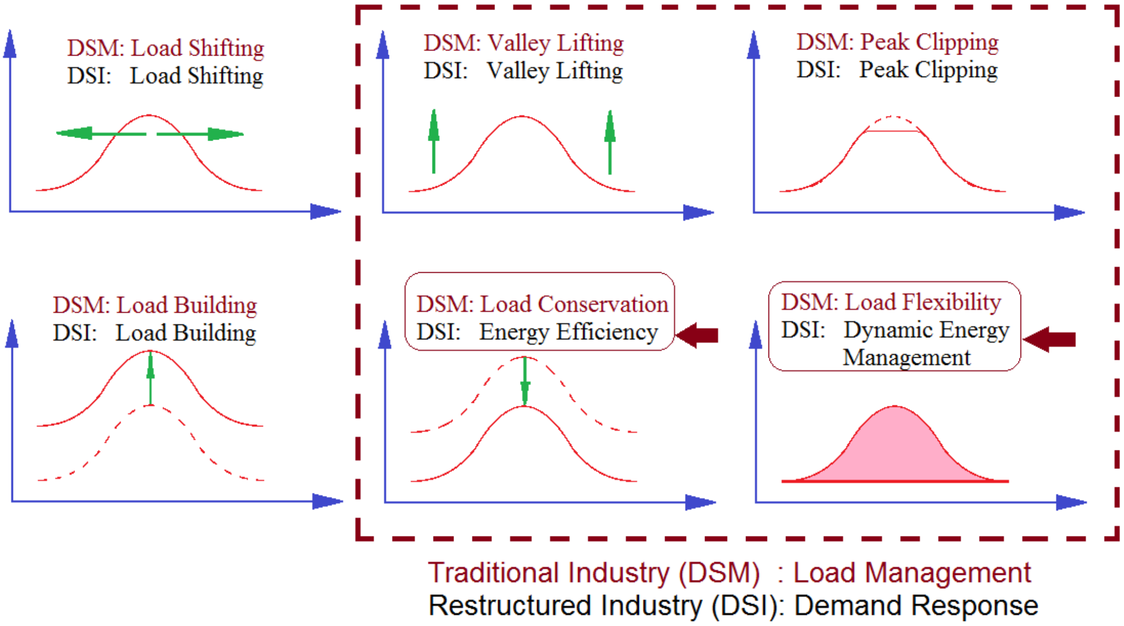
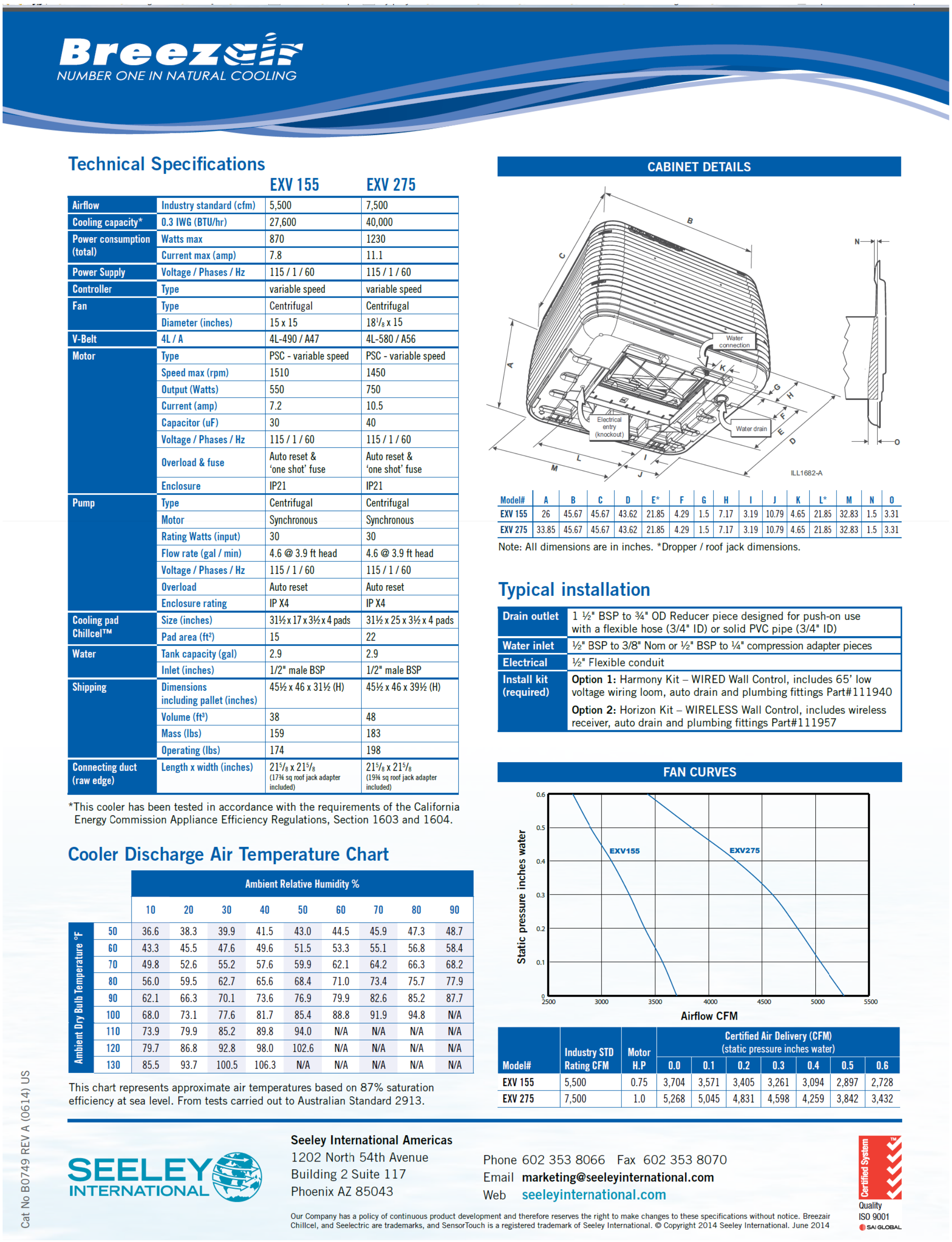


Figure E.1: Demand Side Management terminology [250].

Appendix (F) Breezair EXV-155 specifications



Technical Specifications

		EXV 155	EXV 275
Airflow	Industry standard (cfm)	5,500	7,500
Cooling capacity*	0.3 IWG (BTU/hr)	27,600	40,000
Power consumption (total)	Watts max	870	1230
	Current max (amp)	7.8	11.1
Power Supply	Voltage / Phases / Hz	115 / 1 / 60	115 / 1 / 60
Controller	Type	variable speed	variable speed
Fan	Type	Centrifugal	Centrifugal
	Diameter (inches)	15 x 15	18⅛ x 15
V-Belt	4L / A	4L-490 / A47	4L-580 / A56
Motor	Type	PSC - variable speed	PSC - variable speed
	Speed max (rpm)	1510	1450
	Output (Watts)	550	750
	Current (amp)	7.2	10.5
	Capacitor (uF)	30	40
	Voltage / Phases / Hz	115 / 1 / 60	115 / 1 / 60
	Overload & fuse	Auto reset & 'one shot' fuse	Auto reset & 'one shot' fuse
	Enclosure	IP21	IP21
Pump	Type	Centrifugal	Centrifugal
	Motor	Synchronous	Synchronous
	Rating Watts (input)	30	30
	Flow rate (gal / min)	4.6 @ 3.9 ft head	4.6 @ 3.9 ft head
	Voltage / Phases / Hz	115 / 1 / 60	115 / 1 / 60
	Overload	Auto reset	Auto reset
	Enclosure rating	IP X4	IP X4
Cooling pad Chillcel™	Size (inches)	31½ x 17 x 3½ x 4 pads	31½ x 25 x 3½ x 4 pads
	Pad area (ft²)	15	22
Water	Tank capacity (gal)	2.9	2.9
	Inlet (inches)	1/2" male BSP	1/2" male BSP
Shipping	Dimensions including pallet (inches)	45½ x 46 x 31½ (H)	45½ x 46 x 39½ (H)
	Volume (ft³)	38	48
	Mass (lbs)	159	183
	Operating (lbs)	174	198
Connecting duct (raw edge)	Length x width (inches)	21⅝ x 21⅝ (17¾ sq roof jack adapter included)	21⅝ x 21⅝ (19¾ sq roof jack adapter included)

*This cooler has been tested in accordance with the requirements of the California Energy Commission Appliance Efficiency Regulations, Section 1603 and 1604.

Cooler Discharge Air Temperature Chart

Ambient Dry Bulb Temperature °F	Ambient Relative Humidity %								
	10	20	30	40	50	60	70	80	90
50	36.6	38.3	39.9	41.5	43.0	44.5	45.9	47.3	48.7
60	43.3	45.5	47.6	49.6	51.5	53.3	55.1	56.8	58.4
70	49.8	52.6	55.2	57.6	59.9	62.1	64.2	66.3	68.2
80	56.0	59.5	62.7	65.6	68.4	71.0	73.4	75.7	77.9
90	62.1	66.3	70.1	73.6	76.9	79.9	82.6	85.2	87.7
100	68.0	73.1	77.6	81.7	85.4	88.8	91.9	94.8	N/A
110	73.9	79.9	85.2	89.8	94.0	N/A	N/A	N/A	N/A
120	79.7	86.8	92.8	98.0	102.6	N/A	N/A	N/A	N/A
130	85.5	93.7	100.5	106.3	N/A	N/A	N/A	N/A	N/A

This chart represents approximate air temperatures based on 87% saturation efficiency at sea level. From tests carried out to Australian Standard 2913.

CABINET DETAILS

Model#	A	B	C	D	E*	F	G	H	I	J	K	L*	M	N	O
EXV 155	26	45.67	45.67	43.62	21.85	4.29	1.5	7.17	3.19	10.79	4.65	21.85	32.83	1.5	3.31
EXV 275	33.85	45.67	45.67	43.62	21.85	4.29	1.5	7.17	3.19	10.79	4.65	21.85	32.83	1.5	3.31

Note: All dimensions are in inches. *Dropper / roof jack dimensions.

Typical installation

Drain outlet	1 ½" BSP to ¾" OD Reducer piece designed for push-on use with a flexible hose (3/4" ID) or solid PVC pipe (3/4" ID)
Water inlet	½" BSP to 3/8" Nom or ½" BSP to ¼" compression adapter pieces
Electrical	½" Flexible conduit
Install kit (required)	**Option 1:** Harmony Kit – WIRED Wall Control, includes 65' low voltage wiring loom, auto drain and plumbing fittings Part#111940 **Option 2:** Horizon Kit – WIRELESS Wall Control, includes wireless receiver, auto drain and plumbing fittings Part#111957

FAN CURVES

Model#	Industry STD Rating CFM	Motor H.P	Certified Air Delivery (CFM) (static pressure inches water)						
			0.0	0.1	0.2	0.3	0.4	0.5	0.6
EXV 155	5,500	0.75	3,704	3,571	3,405	3,261	3,094	2,897	2,728
EXV 275	7,500	1.0	5,268	5,045	4,831	4,598	4,259	3,842	3,432

Cat No B0749 REV A (0614) US

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