Hydropower in Scotland: Linking changing energy and environmental agendas with sustainability outcomes

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STATEMENT OF ORIGINALITY

I hereby confirm that this PhD thesis is an original piece of work conducted independently by the undersigned and all work contained herein has not been submitted for any other degree.

All research material has been duly acknowledged and cited.

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GENERAL ABSTRACT

As the UK energy sector moves to a greater contribution from low-carbon and renewable sources it faces significant challenges in delivering affordability, security of supply and sustainability. Although hydropower in Scotland emerged on a large scale in the mid-20th century against an influential, changing wider context of energy policy, environmental regulation and debate, it is now subject to an evolving renewables agenda. This further shapes the national and scheme level characteristics of hydropower and in turn outcomes for the water environment. Contingent upon these considerations, hydropower regulation must now deliver on EU obligations to protect and improve the ecological status of water bodies, whilst also supporting domestic efforts to meet high profile binding renewable energy targets.

Yet, despite an acknowledged potential for energy policy to constrain the delivery of water policy objectives, there is little policy harmonisation between disciplines. As Scotland orientates itself as a leader in Europe on climate change, transitioning to increasing amounts of renewable generation across a handful of technologies, there is a gap in knowledge about how specific renewable policies and trends can influence hydropower sustainability outcomes and regulatory challenges.

This thesis therefore contributes an innovative and timely critical examination of the effect a changing wider renewable energy and policy context has on hydropower sustainability in Scotland, at a scheme and national level. This research uses an interdisciplinary, temporal analysis to identify linkages and create dialogue between disciplines and scales, informing the pursuit of sustainable renewable energy through policy and regulation in a changing world.

It finds firstly, that the changing national generation mix towards an increased contribution from renewable sources, including potentially intermittent technologies such as wind power, has contributed to an alteration in the operational characteristics and reservoir variability profile of

Cruachan pumped-storage scheme, presenting positive outcomes for reservoir littoral habitats. Secondly, it finds that whilst not operating in isolation, renewable energy incentive policies, through their eligibility criteria, financial reward frameworks and timing, influence hydropower characteristics and sustainability challenges, providing trade-offs but also synergies for hydropower regulation. Finally, it finds that there is a degree of divergence in hydropower outcomes and challenges in Scotland and Norway, due to the characteristics and especially interaction of wider contextual elements such as topography, profile of precipitation input, national energy needs and the role of regional and municipal government. By highlighting these linkages, this thesis is of value to energy policy and environmental regulation in Scotland and across the EU, and is seen as a first step in addressing these uncertainties and supporting a more integrated and sustainable hydropower and renewables governance framework.

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ANACRONYMS AND ABBREVIATIONS

BBM	Building block methodology
CAR	Water Environment (Controlled Activities) Regulations (2005)
CEDREN	Centre for Environmental Design of Renewable Energy
CEH	Centre for Ecology and Hydrology
CF	Capacity factor
Cusecs	Cubic feet per second
DECC	Department for Energy and Climate Change (DECC)
DTI	Department of Trade and Industry
EC	European Commission
EU	European Union
FDC	Flow duration curve
FiTs	Feed-in Tariffs
GWh	Gigawatt Hour
IEA	International Energy Agency
IPCC	International Panel on Climate Change
kWh	Kilowatt Hour
km	Kilometres
LLTNP	Loch Lomond and the Trossachs National Park
m	Metre
m.g.	Million gallons
m.g.d	Million gallons per day
$m\ s^{-1}$	Metre per second
MCT	Marine Current Turbine
MoE	Norwegian Ministry of Environment
MoPE	Norwegian Ministry and Petroleum and Energy
MW	Megawatts
MWh	Megawatt hour
NEA	National Ecosystem Assessment
NDSFB	Nith District Salmon Fishery Board
NFFO	Non-fossil Fuels Obligation
NoSHEB	North of Scotland Hydroelectricity Board
NVE	Norwegian Water Resources and Energy Directorate
OECD	Organisation for Economic Co-operation and Development
Ofgem	Office for Gas and Electricity Markets
RBMP	River Basin Management Plan
RO	Renewables Obligation
RO(S)	Renewables Obligation Scotland
ROC	Renewables Obligation Certificate
RPI	Retail Prices Index
StDev	Standard deviation
SEPA	Scottish Environment Protection Agency
SINTEF	The Foundation for Scientific and Industrial Research
SNH	Scottish Natural Heritage
SNIFFER	Scottish and Northern Ireland Forum for Environmental Research
SSE	Scottish and Southern Energy
SRO	Scottish Renewables Obligation
TWh	Terawatt hour
UKCIP	UK Climate Impacts Programme
UK TAG	UK Technical Advisory Group

WCED	World Commission on Economic Development
WFD	Water Framework Directive
WLDC	Water level duration curve

TABLE OF CONTENTS

CHAPTER ONE: INTRODUCTION

CHAPTER TWO: LITERATURE REVIEW

CHAPTER THREE: CRUACHAN PUMPED STORAGE SCHEME – CAUSES AND POTENTIAL IMPLICATIONS OF A SHIFTING OPERATIONAL PROFILE

CHAPTER SIX: DISCUSSION

CHAPTER SEVEN: CONCLUSION

REFERENCES

LIST OF FIGURES

LIST OF TABLES

MAPS

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

Alongside internationally recognised areas of high ecological and landscape value and diversity, Scotland has an abundant provision of water resources, which continue to play an important role in its economic development and contributing towards its cultural identity as a “hydro nation” (Scottish Government, 2012b).

With a temperate maritime climate, high annual rainfall that in the western Highlands can rank amongst the highest in Europe (Johnson, 1994), generally modest evaporative demands (Marsh and Anderson, 2002), and although diverse, an often steep topography, there is a high runoff per unit area (Gilvear et al., 2002). Indeed, situated in the northern third of the Great Britain, Scotland’s hydroclimate is often more akin to that of north Atlantic countries (Roald, 1998).

Reflecting this enviable natural hydrological resource base, it is not surprising therefore that Scotland has a long history of river flow utilisation and regulation to serve a range of societal needs, including electricity generation through hydropower. Utilising the volume of flow and a drop, or head in a water body, hydropower has long offered a cheap and readily available source of electricity for Scotland.

1.11 The emergence and development of hydropower in Scotland

The first hydropower plant for public supply in Scotland was in 1885 in Greenock, Renfrewshire, followed in 1890 by an 18kW scheme constructed by monks at St Benedict’s Abbey at Fort Augustus (Payne, 1988), both serving to demonstrate the resource potential and technical feasibility. The development of hydropower on a national scale followed in the 20th century, with an initial phase of private development supporting the aluminium smelting industry in the 1920s, then the most significant expansion of hydropower in the 1950s and 1960s under the North of Scotland Hydro-

Electricity Board (NoSHEB). In the fifteen year period from 1950 to 1965, 74 hydropower installations were constructed totalling over 950MW in capacity (DECC, 2012a), with the NoSHEB period of development comprising 66 dams, 103 miles of aqueducts and 171 miles of tunnels (Payne, 1988).

Against efforts to reduce the amount of greenhouse gas emissions from finite fossil fuels that contribute to anthropogenic climate change, hydropower in Scotland has over the last 25 years undergone further expansion and an increased profile as a source of renewable energy under the climate agenda. Although in magnitude relatively small on a global scale, with 3.3TWh in production and 1.4GW in installed capacity in 2010 (Scottish Government, 2012), as a contribution of total national electricity generation, Scotland is in the top ten hydropower countries worldwide (IEA, 2011). This contributes to Scotland's orientation as a leader on renewables in Europe (Scottish Government, 2011).

Indeed, delivered in the main by schemes constructed in the NoSHEB phase of development, hydropower supplied 34% of renewable and 7% of *all* generation in Scotland in 2010 (Scottish Government, 2010). Scotland is also the principal generator of hydropower in the UK, supplying over 90% of 2010 production (DECC, 2012), forming parallels with other natural resource rich countries in north-western Europe such as Norway.

1.1.2 Trade-offs from hydropower

A river's natural flow regime is the range of natural flow variability (Poff et al., 1997; Richter et al., 2003) that shapes downstream physical, chemical and biological characteristics, and around which aquatic ecology has evolved lifecycle characteristics (Bunn and Arthington, 2002). By harnessing the flow of a river for electricity generation however, hydropower of all scales alters a river's natural flow regime, causing a disequilibrium and an associated river response away from natural conditions, and often a loss of ecological diversity and integrity (Petts, 1979). There are also implications for landscapes and aesthetics (SNH, 2010b), and a wider tension of scale between national climate benefits and local level tradeoffs.

As a result, governance mechanisms must reconcile the energy benefits of hydropower with these potential tensions and trade-offs for freshwater and natural heritage integrity (Reid et al., 2004). Indeed, it is this necessary balance in approach, to deliver on hydropower resource potential and contributions to renewable energy targets, whilst also minimising trade-offs, taking a proportionate and justifiable approach, and maintaining water ecosystem health and service value, that has led Scottish Ministers to advocate for *sustainable* renewable energy (Scottish Government, 2012).

1.1.3 The significance of a changing wider context for hydropower

The historical emergence and continuing development of hydropower in Scotland has meant it is exposed to a changing wider context of energy policy and environmental regulation and debate. This in turn has shaped its characteristics at a national level, but also influences the design, mitigation and operational approach of individual schemes.

With the trade-offs and implications from hydropower shaped by local hydrological conditions (e.g. Gilvear et al., 2001; Marsh and Anderson, 2001), but also scheme design and operational characteristics (Petts, 1984), we can see that understanding the influence of this wider context is crucial for delivering sustainable hydropower in Scotland.

By critically examining the influence of this changing energy and water context on hydropower characteristics and challenges, this thesis seeks to provide an interdisciplinary understanding of the long term sustainability of hydropower in Scotland, and to inform regulatory and policy challenges and approaches in a changing world.

1.2 CONCEPTUALISING THE PROBLEM

Under the 2009 EU Renewable Energy Directive (2009/28/EC), the UK is committed to a series of binding targets, including a 20% increase in the use of renewable energy by 2020. As we move to a greater contribution from low-carbon and renewable sources, the UK energy sector faces significant challenges in delivering an affordable, secure and sustainable energy system (Ofgem, 2012a).

The Scottish Government has shown strong climate leadership through the far reaching Climate Change (Scotland) Act 2009, setting ambitious targets including reducing green-house gas emissions by 42% by 2020, against a 1990 baseline. Building on a significant natural resource base, Scotland is displaying increasing divergence in energy strategy from the rest of the UK, ruling out any new nuclear build and committing itself to increasing amounts of renewable energy, setting an ambitious domestic aspiration to generate 100% of electricity used from renewables by 2020. This energy autonomy carries additional political significance with a Scottish National Party in government in Holyrood, and a referendum for Scottish independence from the UK being held later in 2014.

Delivery of renewable generation in the UK is supported by financial incentive policy mechanisms, with the evolving 2002 Renewables Obligation the main support mechanism for large scale renewable deployment, and the 2010 Feed-in Tariffs serving domestic and community generation. Through differing approaches to eligibility and the way they support renewables including hydropower, incentives can shape national level and scheme characteristics, leading to implications for water resource regulation.

Under these strong drivers and renewables agenda, Scotland therefore has seen a response in the wider electricity generation mix, with reduced emphasis on traditional large fossil fuel base load stations, towards increasing amounts of renewables, specifically a growing proportion of potentially intermittent wind generation.

Delivering over 10% of all generation in 2012 (Scottish Government, 2012) and projected to supply over 40% by 2020 on a medium uptake scenario (Scottish Government, 2011), this transition towards increasing proportions of wind generation, presents challenges in terms of efficiently integrating generation output with wider demand profiles (IEA, 2005). This shift in turn has put a greater value on existing storage capabilities that seek to match supply to demand, such as pumped storage hydropower (Scottish Government, 2010b), with the alteration of operational profile (Deane et al., 2010) and consequently reservoir handling away from traditional approaches (Wolfgang et al., 2009; Knudsen and Ruud, 2011) to meet changing grid needs. Future additional capacity is also being pursued, through the recently proposed 600MW pumped storage scheme at Coire Glass, and scoping being undertaken in early 2014 to identify the potential for increasing the capacity at Cruachan pumped storage scheme.

By adding spatial and technological diversity, or through active management elements such as pumped storage hydropower, the UK distribution grid works to deliver supply from the generation mix to meet demand at minimised operation costs (both economic and environmental) (IEA, 2005).

Grid interconnectors link generation to supply regions within the UK, but also internationally, with the UK connected to Ireland, France and the Netherlands. The energy transition towards increased renewable generation in the UK and across Europe means that connectivity is central to future energy integration and security issues. A further interconnector is being planned to link the UK and Norway, serving the 'battery for Europe' agenda (Solvang et al., 2012) where Norway can open up its own hydropower storage schemes to balance intermittent generation elsewhere across Europe.

This trend for increased international connectivity and 'opening up' of national generation grids presents uncertainty regarding Scottish hydropower as it is suggested elsewhere that a changing energy context can alter the operational profile (Deane et al., 2010) and consequently reservoir handling of existing peaking schemes away from traditional approaches (Wolfgang et al., 2009; Knudsen and Ruud, 2011).

These trends are part of a wider crucial period for UK electricity supply, as against this significant increase in contribution from wind, although still minimal, there is a slightly heightened risk to security of supply over the short term to 2016. This is due to no new conventional plants planned, industry announcing the withdrawal of over 2GW of capacity, and investment uncertainty around policy and future prices (Ofgem, 2013b).

This examination of the emergence and sustainability of hydropower in Scotland is informed further through a comparison of the hydropower experience in Norway. With a similar historical emergence (Angell and Brekke, 2011), comparable political and regulatory commitment to sustainable renewable energy (Knudsen and Ruud, 2011), and Scotland (Scottish Government, 2010b) and Norway (Solvang et al., 2012) both recently revisiting hydropower as a means to integrate further renewable generation, the comparison makes for a useful and timely assessment.

1.2.1 The water environment

This evolving wider energy context of socio-economic and energy policy trends shapes the characteristic of hydropower and in turn the implications and pressures on water resources, informing environmental tensions and outcomes (Volkery et al., 2011). Despite this, however, in general over OECD countries there is little harmonisation and sufficient consideration of the interrelation between energy and water and environment policy areas and frameworks (OECD, 2011), presenting a risk for unsustainable outcomes and trade-offs.

In parallel to obligations under the EU's Renewable Energy Directive, Scotland must also deliver protection and improvements to water bodies under the Water Framework Directive (WFD) (2000/60/EC). To meet objectives for water bodies, Member States must apply WFD to future hydropower proposals, but crucially also must review existing licences to secure improvements to ecological conditions. Other high profile habitats and species protection is provided through the European 'Habitats Regulations' (Habitats Directive 92/43/EEC, and Birds Directive 2009/147/EC).

In a similar vein to that on climate change leadership, the Scottish Government also seeks to orientate Scotland as a 'Hydro Nation' to realise, protect and deliver on the high value of the water environment and sector, in a changing and often stressed hydrological world (Scottish Government, 2012b). The changing role and potential sustainability of hydropower is therefore a significant consideration in this context for its delivery of services and social value, but also its potential to reduce the functioning and ecological integrity of valued hydrological systems. Indeed, there is a wider trend towards a greater economic and societal appreciation of the value of the water resources in the UK, so as to be better equipped to inform environmental decision making (NEA, 2011).

This theme and challenge of regulating in a changing world is reflected through the Living with Environmental Change (LWEC) research council agenda, which highlights that water quantity and quality, alongside fuelling the energy debate, are two areas of high importance in the current and near future (CERF, 2012).

Against this often changing and evolving background, and given the lack of harmonisation (OECD, 2011), but significant interaction between water and energy policy areas, affecting the potential to deliver on environmental targets (Volkery et al., 2011), it is argued here that understanding this specific connectivity and mechanisms of influence is central to delivering sustainable hydropower in Scotland.

1.3 RESEARCH PROBLEM

The study of hydropower and its influence on rivers is characterised by change, and its exposure to it. Be it the potential for a lagged response in downstream conditions (Petts, 1979); the changing perception and prioritisation of impacts (Reid et al., 2004); the uncertainty surrounding climate change and in turn water resource decision making (Werritty, 2002); or the evolving and influential renewables agenda (Ofgem, 2011), there is an inherent temporal aspect which must be considered.

In the evolving renewable energy paradigm as further capacity and delivery is pursued across a number of technologies, as renewables become a larger percentage of the mix, and established technologies have a greater proportion of their resource potential developed, issues of sustainability become even more important.

Put simply, hydropower governance is in a challenging position because it must satisfy often competing energy and environmental policy goals. However, additional complexity arises as these changing wider frameworks and context also shape and influence hydropower outcomes themselves, at a national and scheme level. With the lack of wider policy harmonisation (OECD, 2011), yet the potential for interaction and trade-offs for water and environmental policy (Volkery et al., 2011), understanding the connectivity and way in which the wider changing energy agenda shapes scheme level environmental outcomes is crucial for integrative decision making and sustainable renewable energy.

In its basic form, sustainable development is development that meets the needs of the present, without compromising the ability of future generations to meet their own needs, reflecting environmental, economic and social elements (WCED, 1987). This outlook embodies an appreciation of the finite nature of environmental resources and carrying capacity, but also the interdisciplinary, multi scale and temporal nature of sustainability challenges.

Sustainability as a concept is therefore very important for hydropower in Scotland as the sector navigates and reconciles often competing energy and environmental policies, delivers on valuable natural resource potential, and meets national level priorities and local level challenges.

This theme of balance can be seen in the 2010 energy policy statement (Scottish Government, 2010), which sets out that the benefits of hydropower generation must be considered along with the protection of the water environment. Similar elements of proportionality and justifiability are included in SEPA's hydropower licencing framework, where proposed schemes are screened by weighing the annual generation contribution against the length of river that is adversely affected. In this way, it is only permissible for a short length of river to be adversely affected for schemes generating 0.35 to 1.75GWh annually, around the 100kW capacity (SEPA, 2010).

Reflecting this challenge for hydropower regulatory and governance frameworks in Scotland, this thesis engages with the theme of renewable energy sustainability, and sustainability outcomes. Sustainability outcomes in this context are therefore occurrences where trends or interactions in the wider context for hydropower result in positive or negative outcomes for sustainability of this kind. Engaging in such outcomes informs awareness of the effect of interactions and linkages between disciplines and scales, and allows for more integrated decision making, sustainability improvements and gains in environmental efficiency.

Despite the Brudtland report being issued over 20 years ago, it is argued that attempts to solve environmental and sustainability issues are still regularly approached in isolation and all too often result in perverse or unforeseen consequences elsewhere (SDC, 2011). With the mandate for climate mitigation becoming stronger, this thesis takes this same critical view. To deliver and maintain sustainable renewable energy therefore, it is necessary to have full awareness of, and communicate how, the wider energy and environmental agenda shape the characteristics and outcomes of hydropower, and understand how current trends will shape this into the future.

Figure 1.0 sets out this research approach as a simple diagram. It conveys the mechanism that a wider context can shape hydropower outcomes and challenges, at a scheme and national level, through shaping hydropower characteristics. There is also the potential for a feedback loop where outcomes and challenges for sustainability can feedback to the wider context, such as through governance frameworks. Indeed, if a given wider *energy* policy led to specific outcomes and challenges for environmental regulation, this may feedback to shape *environmental* policy.

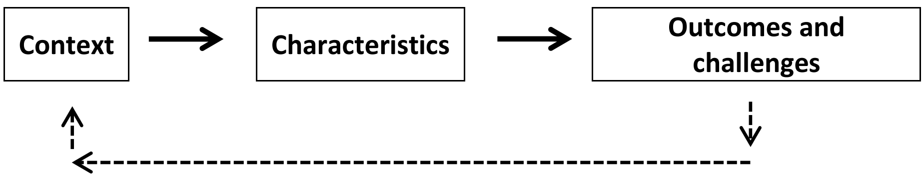


Figure 1.0: Research framework for this study

1.4 RESEARCH PARAMETERS

This research is utilising a longitudinal perspective to critically examine the effect of a changing wider context on hydropower sustainability in Scotland. The main focus will be on hydropower schemes, regulation and challenges in Scotland, but as energy policy in the UK is a reserved matter, some of the wider consideration of energy context and trends will be on a UK and European level.

The historical emergence and continual development of hydropower in Scotland provides a basis to the framework for this study, which will consider hydropower in the initial pioneering phase of development in the 1920s, followed by the NoSHEB period, and more recently the climate led renewables era. Developments in energy policy, such as the changing UK energy mix and renewables incentive mechanisms, as well as in hydropower governance and water regulation, such as the WFD and domestic transposition, also provide temporal elements that shape the parameters of this study. The consideration of sustainability trends are also applied to the future, with recommendations for regulation where possible, to inform continuing and emerging challenges for Scotland.

This research will very much be interdisciplinary in approach, but crucially will explore the linkages between disciplines and scales. To do so, it will examine elements of European and national policy, both energy and environment, but also consider scheme characteristics, mitigation and operational profile, in addition to environmental outcomes in terms of hydrological indices and pressures on specific habitats and species.

As there is little or no previous work looking into the influence of a wider changing energy context on hydropower sustainability and regulatory outcomes, this thesis is in places a first step in identifying and engaging with the linkages between disciplines and scales. Due to time and resource constraints it is unable therefore to engage in overt economic and social aspects, which commonly come under the umbrella of sustainability more widely. For the same reason, this thesis is unable to engage in quantitative aspects of sustainability reporting, which could follow on from the analysis provided here to set out a numerical basis to the trade-offs or synergies, perhaps in terms of a reduction in carbon emissions (tonnes/yr) or stretches of rivers degraded (km).

As a first step into this field with reference to hydropower in Scotland, this research does engage with and seeks to inform the challenge of delivering sustainable renewable energy in a changing world. Providing significant opportunities and recommendations for future research and policy needs, with the dynamic of sustainability outlined above, this research will seek to identify and examine trade-offs, regulatory challenges, trends in environmental impact and trajectory, and inefficiencies or indeed efficiencies and synergies.

Again this is explored on multiple scales, and could emerge as high level policy tension and conflict, on a strategic perhaps theoretical level, or indeed as scheme level habitat and species pressures.

Given this interdisciplinary approach, and focus on connectivity between disciplines and scales, the methodology and sources of data for the thesis will be very varied, and indeed differ by chapter. Policy frameworks and instruments will be considered alongside regulatory guidance documents, and reported data from public bodies on relevant energy, water resource and scheme trends and characteristics. Archival work provides insight into the functioning of NoSHEB, and reservoir level data is assessed for the Cruachan case study.

1.5 RESEARCH AIMS AND OBJECTIVES

The aim of this research is:

To provide an interdisciplinary understanding of the long term sustainability of hydropower in Scotland, identifying the influence of a changing energy and water context on hydropower characteristics and challenges.

The objectives of this research are:

- To critically assess the role of the wider electricity generation mix in shaping operational characteristics and reservoir variability profile, through the example of Cruachan pumped-storage scheme.

- To examine the role of renewable energy incentive mechanisms in shaping hydropower characteristics and outcomes, at a national and a scheme level.

- To assess the trajectory and potential divergence of hydropower characteristics and approaches in Scotland and Norway.

1.6 THESIS STRUCTURE

To serve the thesis goal of critically examining the influence of a changing wider context on hydropower sustainability outcomes in Scotland, this thesis first of all will consider the broader literature base of understanding related to hydropower impacts and challenges. In relation to the aim of this research, this is a fairly broad area of literature, encompassing work on natural flow regimes and their significance; hydropower, dams and environmental impact; and the study of hydropower in Scotland for example.

The research element of this thesis is divided into three chapters that each deliver on one of the above research objectives, but serve the wider research aim. A fuller justification for the inclusion, focus and orientation of each of the three research chapters is provided within those chapters themselves. As stand alone pieces of research, they examine a particular element or trend, utilising often different data and research approach, but fitting in with the aim and sentiment of this research. A full introduction is provided at the start of each of the three chapters, which respectively look at the influence of a changing wider electricity generation mix on Cruachan pumped-storage scheme, the role of incentives in shaping hydropower outcomes and regulatory challenges, and a comparison of hydropower context, trajectory and approach in Scotland and Norway.

A discussion and conclusions then follows as a final chapter, bringing together the findings from the research chapters, considering them against the literature review and objectives of this research, and then summarising and highlighting the original contribution this research has made.

CHAPTER TWO: LITERATURE REVIEW

2.1 HYDROPOWER RESEARCH IN SCOTLAND

This literature review will briefly set out the development of hydropower research in the UK, then present the understanding of the impact of hydropower and dams more widely, considering the resulting issues of flow regime change and river response. It will then engage in the linkages between disciplines and the challenge for sustainable water resource use, before setting out some uncertainty and gaps in knowledge regarding the influence of a wider energy context on hydropower outcomes and regulatory challenges.

A key work in mapping out the history of hydropower in Scotland is Payne (1988). This extensive work explores the emergence and central role the North of Scotland Hydro-Electric Board (NoSHEB) played in hydropower development after being established under the Hydro-Electric Development (Scotland) Act 1943. The advent of NoSHEB marks the start of the largest period of expansion, and retains significance as the majority of current capacity was constructed in this 25 year period.

Taking ownership of much of the public NoSHEB capacity after privatisation in 1989, SSE published a document providing a brief history of each of their existing historic schemes in Scotland (Scottish and Southern Energy, 2005). Whilst mainly a promotional publication, this provides a useful orientation to each of their schemes and insight into how SSE seek the schemes to be seen today.

In the mid 2000s, a string of journal articles by collaborating academics assessed the historical emergence of environmental concerns for hydroelectricity schemes in Scotland. Having regard to the changing regulatory and approval mechanisms, Reid et al. (2004; 2005) revisited previous proposals from 1901 till 2004 to identify the historical development and emerging regulatory emphasis towards environmental impacts. Through this work, they identified and mapped out ‘phases’ of environmental consideration, giving insight into the understanding and values of society at the time and how this shaped historic schemes, as well as forming a basis to the contemporary position. Similarly, using this historical profile, Pillai et al. (2005) extend consideration towards how the UK and Scottish Government currently seek to reconcile local impacts with renewable energy benefits, identifying an increasingly broad set of considerations and the conflict often felt between competing environmental goals. Additionally, Reid et al. (2006) investigate the degree to which present regulatory frameworks account for the long term and changeable impacts from historic hydro schemes, through a comparison with other potentially detrimental land uses in Scotland (mineral workings and forestry). Black et al. (2006) scrutinise more specifically the types of environmental flow provision of NoSHEB schemes, and draw comparisons against today's expectations, highlighting some interesting differences and continuing challenges.

A key theme that has emerged through this series of papers is the continuing relevance of historic hydroelectricity schemes, both in terms of their energy contribution, but also their environmental impact. Reid et al. (2006) look therefore at how far present regulatory frameworks account for long term impacts from historic schemes, approved under a previous more environmentally lenient regulatory regime. This work reflects the often varied scientific, policy and social context that historic schemes were approved under. Reid et al interestingly recommends the need to build responsiveness and flexibility into current regulatory frameworks, to drive improvements in existing historic schemes and for projects to be attuned to future social and environmental change. These findings, and the wider methodological integration of a historical paradigm with temporal considerations from river science, provide an interesting and fruitful basis to further research in the area.

Energy policy provides for an interesting, complex and evolving area of study in Scotland due to the governance structures in place. Although officially a reserved matter meaning powers were not devolved to the Scottish Government from Westminster in the 1998 Scotland Act, due to planning being devolved, and Scotland having a different political and natural resource base to the reset of the UK, the Scottish Government is in effect able to shape the direction of energy generation within its borders.

In this current framework, Scotland is represented at European level negotiations as part of the UK, but is able to develop its own energy direction (Scottish Government, 2011) and is for example subject to differing levels of support under the UK wide Renewables Obligation (Scottish Government, 2011a).

This divergent energy policy, with greater emphasis on renewable generation and allowing no new nuclear build, supports the wider agenda of the nationalist government in Scotland for increased political autonomy. It is important to note that the historical emergence and continuing significance of hydropower in Scotland therefore is set against this wider political and governance context.

2.2 UNDERSTANDING HYDROPOWER DAMS AND THEIR IMPACT

Whilst there is a long history of river management and reservoir construction in the UK, in-depth investigations into their impact occurred much later following the general expansion of scientific activity and frameworks in addition to the growth of quantitative research methods (Petts and Gurnell 2005). In a review of channel change investigations since 1960, Carling (1988), as well as Gregory and Walling (1973) separately, state that as a result, pre-impoundment data on channel geometry and even river flow records, are few and far between.

Petts and Gurnell (2005) therefore described early understanding of the geomorphological effects from dams as emerging in two phases. The first is before 1950, where there was little field data on the impacts of the then rare large schemes, but there was an awareness by engineers of the potential for temporarily and spatially localised channel degradation, and also the negative impacts of impoundment on fish and salmonid migration, which became a high profile and common consideration (Petts, 1984). This was then developed post 1950, following from a significant increase in the rate of large dam construction, peaking in 1968 (Beaumont, 1978), in addition to the development of scientific measurement and process studies, which became pervading features of fluvial geomorphology research (Petts and Gurnell, 2005). As information and concern for the effects of reservoirs on river channels grew, so did the appreciation for a greater temporal and spatial extent to these riverine impacts in scientific literature (Brandt, 2000).

Leopold and Maddock (1953), cited in Petts (1979), provided geomorphological evidence as to the existence of an equilibrium between river geomorphology and the independent variables of discharge and sediment load. This concept of balance of channel form with catchment processes, and the subsequent channel-change response to imbalance, or disequilibrium, has long provided the central element in river change research (Petts and Gurnell, 2005). Authors such as Richardson and Simons (1976) and Blench (1969) further highlight this balance between forcing function, process and response.

This channel change process is conceptualised by Lane (1955) into a formulaic model, which describes how disruption in discharge regime, depending on local conditions and thresholds, could lead to channel aggradation or degradation, and local channel form adjustment. Schumm (1977), through work on this central concept in the study of regulated rivers, further highlighted the role of spatially and temporally distinct geomorphic thresholds, which would not be exceeded simultaneously, leading to a lagged riverine adjustment response to impoundment. Petts (1979; 1980b; 1982; 1987) further outlined factors that lead to complex spatial variations of channel response (e.g. sediment heterogeneity, flow variability), beyond the more readily understood processes and long term adjustment outcomes.

2.3 FLOW REGIME CHANGES

Whilst considering the feedback mechanisms and process-form relationships that were advanced through the development of conceptual frameworks during the 1970s, it is also important to acknowledge the specific ways in which flow and sediment regimes are altered through hydro and impoundment. The evidence of flow regulation provides that dams are society's single greatest point-source hydrological influence, altering flows over a timescale of hours to years (Petts, 1984). Whilst each dam is unique in the profile in which it regulates the natural flow regime, all dams carry out this function in some way, delivering a range of societal goals such as flood control, electricity power generation or industrial water supply (Brandt, 2000).

A pervading feature of impoundment hydropower schemes is the reduction in downstream flow. Richter and Thomas (2007) however suggest that it is useful to differentiate between dams of different purpose, as this will dictate its environmental flow components. Hydropower dams typically ensure a large body of water is created and stored, producing a head of potential energy. Flow is then released at a rate and timing consistent with societal demand, to drive turbines and generate electricity. This primarily causes substantial flow attenuation and a moderation of the both low and peak flow extremes, resulting in an attenuated regime with increased flow homogeneity and reduced natural floodplain inundation (Petts, 1984). However, unnaturally fluctuating flow patterns are also created through the alternation of power generation periods. Moreover, whilst there is an overall reduction in peak discharges and moderation of flood events, a completely different hydrological profile may be created, leading to rapid fluctuation and a 'blocky' appearance in flow hydrographs (Richter and Thomas 2007), a drastically changed temporal profile altering seasonal and daily flow (Petts 1984), and due to stratification in reservoirs bodies' (Petts, 1986), potentially transformed limnological conditions (e.g. pH, temperature, turbidity) (Petts 1984; Preece and Jones 2002; Postel and Richter 2003; Naliato et al 2009).

Variability in river flow and reservoir height is a significant consideration in this thesis as it examines the sustainability implications of hydropower. Reference to the changing 'profile' of variability in river flow, or oscillations in reservoir height, over a range of timescales, is a central part of this investigation into river change and environmental outcomes.

The variability of ecologically significant parameters (King and Brown, 2006) within these changing profiles provides a central mechanism to examine how a changing wider energy context can influence the operational and in turn the ecological implications of hydropower. In this way, the variability in profile is examined over a number of timescales, from hourly oscillations to annual range in reservoir height referred to as drawdown.

Flexible, peaking hydropower schemes that can target demand periods, either through conventional storage reservoirs as with Glendoe, or pumped-storage reservoir operation as with Cruachan, provide increased potential for changes in reservoir and downstream flow profile.

The impoundment of reservoirs like the kind provided by hydropower dams, also causes interference with the conveyance of sediment load down a river system, reducing turbidity (Grimshaw and Lewin, 1980). The degree, or 'efficiency' at which a dam traps sediment from moving downstream has been an ongoing consideration since the early 20th century (e.g. Brune, 1953, as highlighted in Petts and Gurnell, 2005). Petts and Gurnell (2005), citing (Hudson et al., 1949), describe how sediment trapping at the point of impoundment, causing reservoir sedimentation and reducing reservoir capacity, has been acknowledged as problematic since the mid-1920s. Yet they add it was not until the 1960s that reservoir design incorporated additional 'dead space' to increase their life expectancy. Alongside a reduced load and concentration, typically due to filtration, a downstream decrease in grain size of sediments is also expected, (Brandt, 2000).

2.4 RIVER RESPONSE AND CHANGE

Petts (1984) states that rivers are complex physical, chemical and biological systems, where flow regimes, influenced by catchment or land use characteristics, drive river and floodplain characteristics. Having presented literature regarding the conceptualised model for river equilibrium and regime change, then subsequently the ways in which flow and sediment conveyance are altered by dams, it is necessary to consider the specific response of the different physical and biological components of a regulated river.

In considering the impacts of impoundment, Petts (1987) groups these effects into three orders, reflecting their cascading influence through river systems. This is useful as it underlines the influence of the changing inputs, provides a form of categorising effects, and presents the temporal and spatial chronology of impacts necessary to begin to consider mitigation and restoration goals in policy and practice. Under this model, first order changes are those describing the initial changed characteristics of inputs, such as water and sediment discharge. Second order changes follow on from these and include changes to channel form, substrate composition and macrophyte populations, with resulting third order changes being changes to wider fish, invertebrate and biotic populations. Although a lagged physical adjustment or ‘relaxation period’ is common following impoundment, Petts (1987) suggests biotic responses occur at a much faster rate, so will often follow closely behind second order changes, perhaps even before the previous order impacts have been observed.

2.4.1 Geomorphological response to regime change

A hydrograph depicts a river’s unique flow pattern over time and is determined by the climate, geology, topography, vegetation and other natural features of its watershed. All components of a river’s hydrograph, even those flow events that occur infrequently such as once every several decades, contribute to the physical, chemical and biological characteristics of a river. More frequent high flows for example commonly work to shape a river's physical characteristics, whereas low or 'base' flows work to determine the extent of aquatic habitat and provide the conditions for fish spawning migration (Postel and Richter, 2003).

A useful starting point regarding the downstream geomorphological effects of impoundment are the central texts provided by Petts (1979; 1984) and Carling (1988). These works seek to highlight the previously underestimated magnitude of impacts on downstream reaches, and of the previously limited consideration of their spatial and temporal extent.

More recently, Petts and Gurnell (2005) provide an informative review of the development in geomorphical knowledge of channel change below dams, plotting its emergence in the 1950s, development up to the present and potential future research strands. Noteworthy texts are as such grouped into distinct areas; such as the effect on *flows* (e.g. Petts, 1984); *sediment transport* (e.g. Church 2002); the effect on and role of riparian *vegetation* (e.g. Schumm, 1969); the potential for *channel degradation* (e.g. Lawson 1925); and *channel* aggradation (e.g. Gregory and Park, 1974; Petts, 1979). Petts (1984) suggests that a river's adjustment period reflects a complex sequence of adjustments following impoundment, varying spatially and changing with time, but often starting with channel degradation.

The literature sets out that impoundment reduces turbidity as conveyance of sediment downstream is greatly reduced. Consequently, flows downstream of a dam deliver clear water erosion, picking up available sediment from river bed and banks as the flows seek to regain their previous sediment load (Petts, 1984). Channel scouring and degradation have indeed been documented for more than 75 years (Lawson, 1925). Petts (1979) suggests erosion is typically initiated in areas immediately after a dam, and will move down the channel until, either the increase in channel bed roughness following scouring, or the reduction in slope, reduces the velocity below the threshold for sediment transport

(Petts 1979). However, due to the heterogeneity of bed-sediments over their course and over time, Tinney (1962) sets out that the process of channel degradation is complicated by many hydraulic, sedimentologic and biotic factors. Where bed sediment particles exist that are non-transportable by a given regulated flow regime, selective uptake and transport of smaller particles results in an increase in average grain size of bed material, producing a more resistant 'armoured' layer (Harrison 1950).

Petts and Gurnell (2005) cite that flow regulation and moderation due to impoundment, which often lacks seasonal variation and scouring flows, interacts further with riparian vegetation processes, encouraging a deposition and stabilisation of sediment deposits, leading to additional deposition and trapping, further reducing channel capacity. Indeed, the study of channel adjustment to impoundment often engages with the dynamic interaction of geomorphology and ecology following a changed hydrological regime, such as in Gilvear (2004) where confluence bar and bench development interacted with vegetation progressions to facilitate channel narrowing.

2.4.2 Hydrological and ecological responses regime change

The impact of impoundment upon vegetation, as well as the 'feedback' effect vegetation has on a river's physical and chemical characteristics following impoundment, is becoming increasingly understood as a critical element to the study of regulated rivers. In this way, Poff et al. (1997) states the profile of a river's natural flow regime has a dramatic influence on the biodiversity of streams, rivers and the associated floodplain wetlands.

A comprehensive review into understanding of the specific mechanisms that link hydrology and aquatic biodiversity is provided by Bunn and Arthington (2002), illustrating the causal impacts from altered flow regimes. To assists in examining the direct effects of flow regime changes, they group understanding regarding the influence on aquatic biodiversity into four key principles.

The first principle states that flow is a major determinant of physical stream habitat, which means it also sets spatial biotic composition. Considering the moderated, homogenous flow regimes created by impoundment, as described by Petts (1984), Blanch et al. (2000) provide evidence that this causes a growth in plant biomass at the expense of species diversity through a lack of variety in flow, and consequently in habitats, resulting in a shift towards a monoculture. Similarly, flow and subsequent physical habitat change affects aquatic invertebrates through stresses, for example due to rapid fluctuation in daily flow (Munn and Brusven 1991). Bunn and Arthington (2002) identify that this is also the case for fish species where there can be changes to depth, velocity and cover, the most important variables governing habitat complexity and fish species richness. Reflecting this, Bradford (1997) cite that salmon larvae and juvenile salmonids are extremely susceptible to being stranded in rapid unnatural shifts to low flow conditions found in rivers with on-demand hydroelectric power generation, given the 'blocky' hydrological profile as outlined by Richter and Thomas 2007 for example. Saltveit et al. (2001) mirror this position, but add that juvenile fish stranding incidence is not due to this 'hydropeaking' alone, but that temperature, season and light variables also contribute. This therefore has implications for environmental flow and hydro discharge management, with potential for ecological considerations to be factored more readily into hydro operations.

The second principle set out by Bunn and Arthington (2002) is that in response to natural flow regimes, aquatic species have evolved life cycle strategies. Flow plays a central role in species' life events and day-to-day functioning, with patterns of flow being interlinked with life cycle functioning. One example provided by Zhong and Power (1996) where the modified temperature regimes below dams are able to delay spawning in fish, due to the change in seasonal variations and ecological cues that have been established in synergy with the species.

The third principle is the role of longitudinal and lateral connectivity. Bunn and Arthington (2002) state that this is essential for maintenance of habitats and riverine species and can be disrupted through altered flow regimes, leading to population isolation, recruitment prevention and localised extinction. Whilst many other flow variations lead to different biotic responses, the reduced frequency, duration and extent of floodplain wetlands inundation following impoundment, such as outlined by Petts (1984), has been shown to reduce lateral connectivity, floodplain habitat conditions and consequently a decline in waterbird species richness and abundance, for example as cited by Kingsford and Thomas (1995).

The final principle set out by Bunn and Arthington (2002) regarding specific biological impacts stemming from flow regime changes, is that of the interaction of flow regime with the establishment, spread and persistence of exotic and introduced species. Through the relationship between flow and habitat change it is clear the first three principles contribute to create this final dynamic. Bunn and Arthington conclude that the altered flow regimes are able to encourage, favour and facilitate 'external' species to be successfully introduced into local habitats. Specifically, they outline how exotic species' successful colonisation is favoured through processes such as reduced flow variability and increased seasonal stability that stem from impoundment. Moyle and Light (1996) for example found in a study that a small number of fish species that are exotic to an area, being more suited to the moderated homogenous conditions, were as a result able to thrive after being introduced at the expense of biodiversity and native species, which were more adapted to changeable habitat conditions found naturally on the stretch of water when unregulated.

The above consideration of the impacts to flow, geomorphology and ecology underlines how far reaching the influence of hydro impoundment regime change is. It sets out that process-form relationships dictate a river's chemical, physical and biological characteristics, and that following a change to flow regime these characteristics will adjust accordingly over a relaxation period towards a new equilibrium.

This complex process of riverine response, manifest with thresholds and tipping points (Schumm, 1977), feedback relationships (Poff et al, 1997) and the inherent system of geographical conveyance in hydrological systems means that spatial and temporal dimensions are central to understanding the impacts of hydro power on a river system. This dynamic therefore must be reflected not only in our understanding of the timing, significance and distribution of potential impacts, but also in the ways these impacts are contextualised and measured through research.

2.4.3 Rates of change

The rate and degree of morphological adjustments over a relaxation period towards reaching a new quasi-equilibrium is complicated by a complex, adaptive, process-response system. Relaxation times are therefore highly variable and subject to a number of local and wider scale influences (Petts and Gurnell 2005).

Longitudinal data sets and research ensures any hydro installation and its impact are exposed to changing land use, as well as hydrological and climatic conditions (Petts and Gurnell, 2005). This is a theme picked up on by Reid et al. (2004), in relation to assessing the capacity for regulation to reflect these shifting influential variables. Although, Gilvear (2004), mindful of extended river response timescales, suggests climate change could bring about acute relaxation responses to impoundment constructed many decades ago, where increased exceedance of geomorphic adjustment thresholds result from increased flood-rich precipitation events.

There is value therefore in utilising a temporal dimension in hydropower research in the UK. Such a dimension can be applied equally when considering a changing flow variability and regime change, or critically examining an evolving influential wider policy and governance context.

2.4.4 Hydropower impacts and a temporal research paradigm

Research into the impacts of impoundment on rivers in the UK is commonly inhibited by a lack of data describing the catchment and its morphology before flow modification (Petts and Pratts, 1983). The effects of river regulation has nevertheless been a major focus for research (e.g. Gregory and Park, 1974; Petts, 1984; Changxing et al., 1999; Gilvear, 2004).

Gurnell et al. (2003) assert that as river regulation predates the majority of data sets, there is a need for historical analytical techniques to be utilised in this field. This, they add, enables a full assessment of the significance of historical events on catchment changes (e.g. land use change, channelization, peak flow events), enables benchmark conditions to be established and facilitates an assessment of channel response to disturbances.

A number of texts and book chapters contribute to literature in this field, reflecting the need to engage with historical changes in the physical environment (e.g. Trimble and Cook, 1991; Hooke and Kain, 1982; Hooke, 1997). It is often the case that to provide a complete data set for a historical analysis, a variety of data types and sources are integrated. In a text edited by Kondolf and Piegay (2003), the rationale and approach to using topographic surveys and cartographic records (Gurnell et al., 2003), in addition to air photography and remote sensing (Gilvear and Bryant, 2003) is therefore outlined as a means to study river change.

The application of historical methodologies (e.g. cartography, topographic records, aerial photography) have significant value in geomorphological, river habitat and catchment change research (Gurnell et al., 2003). Significantly however, this historical approach can also be applied to archive records, such as Black et al. (2006), to examine management and policy changes, either nationally, or at scheme specific locations.

2.5 CROSS FIELD LINKAGES AND SUSTAINABLE WATER RESOURCE USE

Against this integrative, connective environmental system, many contemporary authors such as Petts (1984), and Postel and Richter (2003) also stress the need for a broader consideration of related variables and impacts in the study of river impoundment. Petts in particular argues for a shift towards longer term analysis, with greater spatial coverage. Given this kind of research landscape, it is understood that a body of literature has arisen that investigates integrative, synergistic water approaches, both in the field and in policy, that meets the needs of more than one policy objective.

Wharton and Gilvear (2006) for example cite that river basin planning is moving to a much more integrative approach, with the Water Framework Directive driving the delivery of multiple benefits in areas that were once viewed as being in conflict, such as ecological health and flood defence. Werritty (2005) investigates the historical development of flood management in the UK, its previous paradigm in ‘hard engineering’, and the progression towards sustainable, integrative flood management, where the importance of managing water, its surrounding environment and land together is articulated.

An appreciation of multiple riverine objectives is also addressed on a more practical basis through Lawson et al. (1991), who consider multiple objective river planning in the analysis of the Roadford Hydropower scheme in Devon. Here a monitoring and refinement of operating procedures regarding the abstraction and storage of water in the scheme’s reservoir is assessed. In this scheme, the impact on downstream physical hydrology is reduced through protection of baseflows, yet energy yield from the scheme is still maintained.

Richter and Thomas (2007) similarly convey the potential to revisit historic dams and to modify their operation to provide social and environmental benefits, whilst still delivering their previous objectives (e.g. energy production). Providing an approach that would meet some of the needs of Reid et al. (2004), who call for a regulatory requirement for the 'review and revision' of historic UK hydro schemes' environmental performance, Richter and Thomas design a framework for planning and implementing a dam 're-operation' project, assessing the hydraulic implications of a scheme, the subsequent impact and then ways in which these can be overcome whilst maintaining the energy production integrity of a scheme.

Whilst authors such as Petts (1984) argue that hydropower schemes primarily lead to flood attenuation, which leads to downstream aggradation and reduced capacity (Gregory and Park, 1974; Petts, 1980), a further consequence of this is conversely that there is a reduced ability for these channels to convey larger flood events. Such a consequence was confirmed by Gilvear (2003) in a study of the River Spey in Scotland. The work of those such as Werritty (2005), and Richter and Thomas (2007) is again therefore of relevance here, as competing water resource interests are managed in sustainable, integrative flood management that works with natural systems.

2.5.1 Expanding the interdisciplinary scope

Environmental integration is not a very commonly used term in the sustainability paradigm, but implies the integration of environmental considerations into all areas of thinking, behaviours and practices (Bührs, 2009). As several EU policy areas interact around the area of hydropower, integration is needed at different levels and scales to avoid conflict and trade-offs with the water policy goals (Water Directors, 2006).

Bührs (2009) argues that despite the growing consideration of environmental issues through the 1970s, and their response through increasing environmental governance, there needs to be an increase in integration. This needs to be done for example to combat environmental problems being shifted or swapped; to decrease inconsistency and inefficiency where environmental measures (legislation, regulation, agencies) overlap; and, to integrate the non-environmental policy sectors (e.g. energy) that influence environmental outcomes (Bührs, 2009). At a policy planning level for example, processes for dialogue and co-operation between the different competent authorities, organisations and stakeholders supports better integration and delivery of hydromorphology (Water Directors, 2006).

Environmental integration however is a challenging notion, both conceptually and in practice, and we need a better understanding of the obstacles of certain scenarios and limitations of particular approaches (Bührs, 2009). It follows therefore that to understand how high profile “environmental” or “green” policies interact, and can lead to unforeseen outcomes, can certainly inform a greater level of environmental integration.

Following the progression of research and understanding regarding the dynamics and implications of flow regulation (e.g. Petts, 1984), then subsequent consideration of the development and application of mitigation through environmental flows (e.g. King and Brown, 2006; Richter and Thomas, 2007; King et al., 2008; Poff et al., 2010), this field has more recently begun to open up to reflect interdisciplinary aspects of water resource use, including hydropower operation.

To deliver on the use value of water resources, whilst making environmental improvements and recommendations, such work must be adaptive, interdisciplinary and science based (Richter et al., 2006). This progression in approach is apparent in a recent special issue of research papers (Bruno and Siviglia, 2012). Here for example research considers, in part, the operational characteristics of a hydropower scheme (Alfredsen et al., 2011), and potential win-win measures for a water supply reservoir and down-stream ecosystems (Yin et al., 2012). To deliver sustainable outcomes, these approaches as such seek to examine and balance aspects of use, with fresh water environmental and stakeholder goals. By doing so, there is an inherent need to engage with the objectives, characteristics and trends of use, but also understand the linkages between disciplines and scales.

Whilst such interdisciplinary assessments can be site specific, such as Alfredsen et al. (2011) that considers operational and stakeholder needs on the Daleelva River in western Norway, this thesis argues that there is also value in extending the interdisciplinary scope to encompass national trends and context, as they can be influential in shaping site level challenges and aspects of use.

For hydropower research to engage in wider energy context, policy and trends, due to its role in influencing site characteristics, operational elements and sustainability challenges, as such presents an innovative further area for development. Indeed, as presented elsewhere in this thesis, despite an acknowledged potential for energy policy to constrain the delivery of water policy objectives (Volkery et al., 2011), there is little policy harmonisation between disciplines (OECD, 2011). This insufficient understanding and appreciation in policy of interrelation between energy and water and environment policy areas is therefore an area for future research, to serve the challenge of sustainable renewable energy in a changing world.

CHAPTER THREE: CRUACHAN PUMPED STORAGE SCHEME – CAUSES AND POTENTIAL IMPLICATIONS OF A SHIFTING OPERATIONAL PROFILE

3.1 INTRODUCTION

Over the last 50 years, the Scottish and UK electricity generation sector has seen significant change in terms of market conditions and the relative contribution from different technologies. This in turn has led to a changing output profile, with implications for the sustainability and security of the electricity supply system as a whole.

Whilst originally developed to integrate the generation profile of large baseload thermal stations, the operational flexibility of Cruachan pumped-storage scheme in Scotland has since allowed alterations to its generation profile, reflecting changing deficit and demand management needs since its construction in 1966 (Sidebotham and Kennedy, 1990). The more recent trend of increased renewable generation, specifically the growing proportion of intermittent wind generation (Scottish Government, 2010b), presents challenges in terms of efficiently integrating generation with wider demand profiles (IEA, 2005). This transition towards a wind dominated renewable era has led to renewed interest in new and existing flexible pumped-storage such as Cruachan, specifically regarding future further shifts in their operational profile to meet the changing grid needs (Deane et al., 2010). However, with hydropower generation patterns at all scales inextricably linked with water resource management (Petts, 1984), a changing pumped-storage generational regime will lead to changes in reservoir handling away from traditional approaches (Wolfgang et al., 2009; Knudsen and Ruud, 2011), and potentially present associated ecological implications (Richter and Thomas, 2007). This research chapter therefore looks to critically examine the effect of a changing national generation mix, and growing contribution of intermittent renewables, on the operational approach and specifically the reservoir handling at Cruachan pumped-storage scheme. From this, operational trends and potential implications for ecology and regulation will be identified.

3.1.1 Cruachan as a case study

Whilst there are numerous base-load generating storage schemes, and indeed more flexible *peaking*-storage hydropower schemes in Scotland, Cruachan is one of only two *pumped*-storage schemes, operating as a net consumer of electricity but playing a vital role in balancing grid output with the national demand profile. Unlike conventional peaking storage schemes, Cruachan operates effectively as a 'sealed system' with reservoir handling and the transferral of water between two storage bodies unaffected by natural hydrological input variability, but rather determined by management decisions regarding generation need (B Wales, pers. comm 22 November 2012).

This scenario acts to control all other variables, allowing a focussed examination of the effect the changing wider energy mix and grid needs have on scheme level decision making and operational approach, and in turn reservoir outcomes. Combined with its operational flexibility, these characteristics at Cruachan mean it is extremely valuable as a case study for this interdisciplinary thesis that looks to understand how wider energy trends and policies can influence hydropower characteristics and environmental outcomes. Furthermore, by limiting the variables in this way, it is argued here that the reservoir trends identified at Cruachan could be applied to the reservoirs of conventional peaking schemes also responding to changing grid needs in Scotland.

To consider the influence of a changing wider energy context on Cruachan, following a section on the background of the scheme and another on developing a robust methodology to examine its changing reservoir variability, this chapter will provide an in-depth historical review of the changing UK and Scottish electricity generation mix. Whilst this history of energy development in the UK and Scotland is lengthy, its inclusion here is justified to clearly identify the changing wider energy context for Cruachan, and to establish the interdisciplinary linkages and perspective as suggested in Richter et al. (2006).

Against this an investigation of the changing operational characteristics of Cruachan since construction is made, through an examination of reservoir level variability. The resulting water level profile will be used as a template to examine potential ecological and regulatory implications for Cruachan. Finally, varying scenarios for renewable penetration into 2020 and 2030 energy portfolios are used to examine the potential future operational demands upon Cruachan. Despite an acknowledged potential for energy policy to constrain the delivery of water policy objectives (Volkery et al., 2011), there is little policy harmonisation between disciplines (OECD, 2011). Therefore, to inform the continuing challenges of reconciling the often competing policy goals of renewable energy development and natural heritage protection, we need to understand the relationship between the changing wider generation sector and resulting operational characteristics, and in turn the ecological outcomes at load following hydropower reservoirs, as shown in **Figure 3**.

Pumped storage, such as Cruachan, and peaking hydro schemes such as Glendoe, are of increasing value for their ability to integrate a greater proportion of renewables into the UK and Scottish generation mix. There has, however, been no research into what kind of challenges this may present for hydropower reservoirs in Scotland. Assessing the potential for ecological implications from a changing reservoir profile will foster communication and explore linkages between energy and water disciplines across all scales, and is of importance for meeting sustainable renewable energy challenges as we transition to a low carbon economy.

3.2 THE CRUACHAN PUMPED STORAGE SCHEME

The majority of current Scottish hydropower capacity is provided by large ‘historic’ conventional impoundment schemes constructed in a phase of development in the 1950s and 60s, totalling over 950MW capacity (DECC, 2012a). This development period came to an end as suitable additional sites were less economical or less acceptable in amenity terms, and conventional thermal and nuclear generation technology became more efficient and cost-effective (Payne, 1988). However, these shifted conditions supported the construction of Scotland's two pumped storage schemes, Cruachan (1966) and Foyers (1974) as they were primarily aimed at energy transfer, balancing the output of conventional thermal and nuclear stations that provide the backbone of electricity generation in the UK (Sidebotham and Kennedy, 1990).

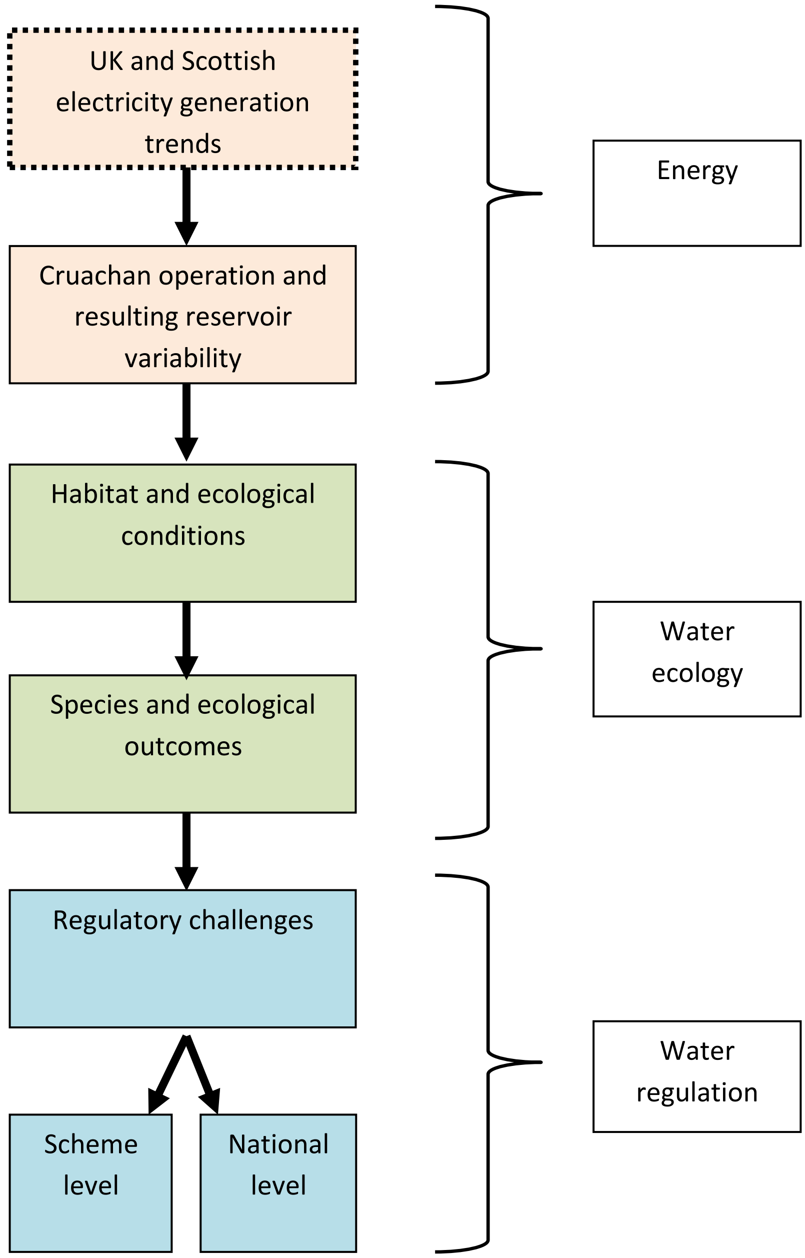


Figure 3: Interdisciplinary linkages associated with this investigation of Cruachan

3.2.1 Site characteristics

The Cruachan pumped storage scheme was developed as part of the conventional Loch Awe hydropower development in 1957, and was the first large scale pumped storage scheme in Scotland (ASCE, 1995). Loch Awe is a large natural reservoir in Argyll and Bute, in Western Scotland, some 20km east of Oban. At its northern extent its steep slopes and the adjacent Ben Cruachan peak (1126m) with natural corrie make an ideal site to support a pumped-storage hydropower scheme.

The upper Cruachan reservoir was created in the small flat corrie on the south side of Ben Cruachan by constructing a 316m wide, 47m high gravity buttress concrete dam, resulting in over 8.46 million m^3 of storage capacity. The upper reservoir on the site of the Allt Cruachan utilises a catchment extended to $23km^2$ through a 19km network of pipes and aqueducts, harnessing flow from the surrounding rivers including the Noe and Liever, with resulting reservoir recharge amounting to 10% of generation. The scheme's lower reservoir is the natural, much larger Loch Awe, which at $1.2km^3$ is the third largest loch in Scotland. Its close lateral proximity to the upper reservoir presents a very attractive and economical head: distance ratio of 1:4 (Payne, 1988) (See **Map 3.0**).

The upper reservoir catchment consists of upland moor and bog, natural woodland and burns. A number of habitats, mammals, plants and insects that are listed for action under the UK Biodiversity Action Plan (UK BAP) are found on Cruachan and the surrounding area. A population of brook lampreys (a BAP species) is found in the upper reservoir, with common lizards also located in the adjacent upland areas. Black throated divers, a noted UK BAP species are also found fishing on Loch Awe (Scottish Power, 2010b). The valued arctic char has also been found in the upper reservoir, having potentially been pumped and accidentally translocated there from Loch Awe (Maitland, 1992). A 1974 sample found no macrophytes in Cruachan Reservoir, due in part to the oligotrophic conditions, and high ranges in water level (Smith et al., 1986).

Map 3.0: The location and site orientation of the Cruachan reservoir

3.2.2 Scheme characteristics

The Cruachan plant itself consists of four independent reversible Francis pump turbine units, two of 100MW, and two at 120MW, served by two underground high pressure shafts 4.8m in diameter between the upper reservoir and the subsurface power station, located in large excavated caverns 400m beneath Ben Cruachan (Fulton, 1966). With the machine floor of the turbine hall 36m below the normal level of Loch Awe, the layout creates an operating head of 365m (Parry and Henderson, 1991).

A 7.5MW induction Pony motor is provided for each of the four turbines to facilitate the 'mode changes', from standstill to generating or pumping. From standstill each machine is able to reach full generating output in two minutes, and full pumping load in eight minutes. However, the Pony motors are able to bring a machine from rest up to a standby synchronous speed, 'spinning in air', allowing a much shorter transition to full generation of less than 28 seconds – providing almost immediate standby capacity (Scottish Power, 2007).

After passing through the turbines the water enters a shared surge chamber, designed to protect the system from sudden influxes. From there, it enters the tail race — a chamber 7m in diameter and more than 900m long. Water from the tail race is discharged into a screen protected forebay area in Loch Awe (Scottish Power, 2010a).

3.2.3 Generation and reservoir handling

Cruachan was constructed at a time when larger base-load thermal plants, and the proposed Hunterston 'A' nuclear station had become increasingly efficient over their predecessors. The Cruachan, and later Foyers pumped-storage schemes offered planned generation. They were, crucially, targeting peak-load demand periods and complemented the baseload output of these larger thermal and nuclear plants (Sidebotham and Kennedy, 1990).

Although providing capacity for around 20 hours continuous generation if necessary (Scottish Power, 2010a), an initial daily load profile was established of a nightly pumping period and two periods of generation in the day, to meet morning and early evening demand peaks, meaning an average of 4-5 load changes per day (approx. 1500 per year) for each of the pump-turbines (Parry and Henderson, 1991). As part of this standardised weekday profile, a pumping period was implemented at weekends reflecting the lower demand and to facilitate reservoir recharge (Fulton, 1966).

As is common with reservoirs of pumped storage schemes, variations in water level of the upper reservoir fluctuate on a daily and hourly timescale in line with this generation approach; they fall when generating and rise through pumping (Smith et al., 1986). This generation load profile therefore determines the profile of reservoir level variability, and thus to a certain extent its outcomes for water ecology (Smith, 1980). However, since its inauguration in 1965, the operational flexibility, and quick standby-response of Cruachan have allowed for a revised generation profile and load regime, catering to changing needs. This altered generation profile, implemented in the mid-1970s, sought to target an increased number of peak periods in the day, resulting in two or three times the original planned number of daily mode changes, up to approximately 4000 per year (Parry and Henderson, 1991).

3.3 INTEGRATING ECOLOGICAL ASPECTS INTO RESERVOIR LEVEL INVESTIGATION

3.3.1 The challenge for water management

A large set of external socio-economic forces, including sectors such as agriculture, industry, energy and tourism, shape the context and pressures on water resources, determining environmental tensions and outcomes (Volkery et al., 2011). The challenge for water resource governance is to reconcile the renewable energy benefits of hydropower, with the tensions and trade-offs for river and reservoir ecosystems (Reid et al., 2004). To deliver sustainable renewable energy, it is critical therefore to understand how the evolving energy context shapes the scheme level operational characteristics of hydropower, and in turn the resulting pressures on the water environment.

3.3.2 Hydrological change within reservoirs

Central to sustainable water resource management is the need to develop and utilise specialist knowledge of the interaction between hydrological processes and freshwater ecosystems (Acreman et al., 2009). A river's 'natural flow regime' is the range of natural flow variations (Poff et al., 1997;

Richter et al., 2003) that shape downstream physical, chemical and biological characteristics, and around which aquatic ecology has evolved lifecycle characteristics (Bunn and Arthington, 2002). Within hydropower regulated flow regimes, a deviation from this balance can therefore result in a loss of ecological diversity and integrity. Whilst this consideration of altered water resource profiles is often in terms of *downstream* river ecosystems, and the magnitude, timing, duration and frequency of river flows (Acreman et al., 2009), water resource characteristics and influence on aquatic systems *within* a reservoir itself are also of relevance (Petts, 1986).

Lakes and reservoirs act as thermal regulators, and nutrient and sediment sinks, with flow dynamics and biological activity affecting often seasonal chemical stratification (Petts, 1986). Significant unnatural fluctuations in reservoir water level, especially where drawdown is large and changes in level are frequent due to hydropower, have for example been shown to be damaging for littoral communities of macrophytes and zoobenthos (Smith et al., 1987).

3.3.3 Identifying implications for reservoir ecology

Against the need to reconcile often competing water resource needs under the Water Framework Directive and renewable energy obligations, it is necessary to consider fully a regulated reservoir's operational regime, including the factors that influence it. Transforming hydrological data into ecologically relevant indices, then again into a format that can aid decision making, is vital (King and Brown, 2006). As with river flow data, the use of specific thresholds (Richter et al., 2006), or more realistically, to overcome ecological outcome uncertainty, *categories* of response to hydrological change (King et al., 2008) can also be applied to deliver ecologically robust, sustainable decision making for a regulated reservoir.

3.3.3.1 Water level regime

Similar to the importance of downstream flow regime (Acreman et al., 2009), lake biota is heavily determined by the magnitude, frequency, timing and duration of water level variability (Bragg et al, 2003). Consequently, changes in the character and rate of water level fluctuations lead to a response in the exposure profile and relative size of littoral and pelagic zones, resulting in changes in littoral macrophyte and zoobenthos populations; invertebrate communities; and fish spawning success (SNIFFER, 2005).

The identification of the most ecologically significant characteristics, and their expression through appropriate parameters, is important to support water resource management research, and to provide robust evidence for decision making at all levels (King and Brown, 2006). The lake component of the Dundee Hydrological Regime Assessment Method (DHRAM) (Black et al., 2000) for example is able to evaluate the degree of anthropogenic impact on surface waters in Scotland, utilising parameters of magnitude, timing, duration and frequency, and also the degree of conformity with the water variability norms identified for Scottish lochs in Smith et al. (1987). Through an investigation of 27 lochs, Smith et al. (1987) identified that very impoverished littoral communities (of macrophytes and zoobenthos) were found in lochs where either:

- The **weekly** range (drawdown) of water level exceeds **0.5m**, or where
- The maximum **annual** range (drawdown) of water level is larger than **5m**

It was found that where both of these criteria coincided, the communities were extremely poor, often absent, and the littoral zone is impoverished.

For pumped and traditional storage schemes, key aspects to investigative work include identifying the range and frequency of water level change, and how this deviates from natural conditions (SNH, 2010). In this regard, it is useful firstly to consider the pathways by which biological quality elements are shaped by reservoir operation characteristics, and specific hydrological parameters (**Table 3**). Loosely highlighting ecological water quality 'needs', this approach displays an underlying philosophy similar to the building block methodology (BBM) (King et al., 2008), which UK regulatory science is set to use more frequently (UKTAG, 2013). This basis is useful for identifying and expressing the important elements of temporal variability in water level change when investigating a lake's ecological value and integrity.

Biological quality element	Nature of deviation from reference condition	Causes	Associated hydrological factors	Hydrological parameters
Macrophytes	Succession in marginal plant communities	Reservoir operation regime	Altered water level, maximum and mean depths	Level (average, seasonal, period water level range); Depth variation
	Reduced growth of submerged macrophytes		High water level	
	Deviations in littoral macrophyte populations		Distortions to character and rate of water level fluctuations	Level (hourly water levels)
Invertebrate fauna	Deviations in benthic invertebrate communities	Reservoir operation regime	Distortions to character and rate of water level fluctuations	Level (hourly water levels)
Fish fauna	High productivity	Reservoir operation regime	Increased lake area and depth	Level (average, seasonal, period water level range); Depth variation
	Distortions to spawning success		Distortions to character and rate of water level fluctuations	Level (hourly water levels) Dynamics of flow

Table 3: Identifying appropriate hydrological parameters relating to biological change due to reservoir operation regime (An extract from Bragg et al. (2003); based on a lit review)

Set against the important elements of water level variability (Bragg et al., 2003) in bold, the resulting significant parameters extracted from **Table 3** are:

Magnitude

- Water level min/max

- Extent of water level change

Frequency

- Number of fluctuations

Timing

- Water level profile

Duration

- Water level duration curve

Note: Each is over a range of timescales (i.e. annual, seasonal, monthly, weekly, daily)

3.3.3.2 Timing and seasonality of water level change

Having identified the relevant parameters for assessing water level regime change, we can add a further temporal criterion to inform the investigation by highlighting periods of heightened habitat sensitivity by being aware of specific valued species' critical life-cycle stages. Through a review of literature and a consultation of expert opinion, Sniffer (2006) provides an overview of a number of species' ecological sensitivity against a seasonal timeframe (**Table 3.1**). For the purposes of this investigation this table has been simplified and 'lake type' has been removed. Although of value in Scotland, the life cycle of various salmon, trout and lamprey species are mostly in riverine environments, so are omitted here.

		Winter				Summer							
Species/ group	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Macrophytes							Growth, flower and seed dispersal						
3-spined stickleback							Nesting						
Pike						Spawning in the flooded eulittoral							
Dragonflies			Nymphs in shallow water										
Charr	Spawning and incubation												
Whitefish, Vendence						Spawning and incubation							
Ruffe								Spawning					
Rudd, Silver bream, Gudgeon, Roach, Crucian carp									Spawning				
Bream, Tench, Common Carp									Spawning				
9-spined stickleback, Rock bass								Nesting					
Common goby								Nesting					

Table 3.1: Sensitivity calendar showing the duration of critical life stages of selected species (SNIFFER, 2006)

Scientific uncertainty and gaps in knowledge often prevent a full understanding of specific ecological outcomes from water level (or river flow) regime change (Werritty, 2002; Arthington et al., 2006; Acreman et al., 2009). Integrating elements of seasonality into this analysis therefore again reflects a BBM type approach and importantly reduces uncertainty by adding further descriptive elements of water regime ecological 'needs', and the timing of potential deviation from them. **Table 3.1** shows that whilst there are critical periods throughout the year, the months of March to July represent an important period for all species groups.

3.4 METHODOLOGICAL APPROACH, LIMITATIONS AND JUSTIFICATION

3.4.1 Methodology

As short term grid management becomes even more important for the economic and environmental efficiency of the UK grid (AEA, 2010), this case study provides a timely examination of the effects of a changing wider generation context on the hydrological management of a pumped storage scheme. It is broken into two parts:

i) Set against an initial historical examination of the changing Scottish and UK electricity generation mix, the first part presents a profile of the changing operational characteristics of Cruachan through an examination of reservoir level variability. The reasons for changes in generation profile will be considered, as will the resulting implications for reservoir ecology where possible.

ii) The second part of the chapter will examine the changing future energy context for Cruachan. This will permit the potential resulting generation approach and reservoir profile to be projected, both as an average and in relation to extreme events. From this projection, we can identify implications for ecology and water resource regulation.

The examination of changing reservoir level variability in **part one** will use a group of available reservoir level data sets (**Table 3.2**), which vary in their resolution and coverage, with most of the data post-dating 2000. Reservoir level analysis will be done through applying commonly used, ecologically significant water level parameters identified in the section above, such as drawdown and water level profile.

Source	Type	Coverage	Resolution
Smith et al., (1987)	Reservoir level benchmark	n/a	Two specific parameters
Smith et al., (1987)	Reservoir level (m)	1975-80	Single parameter figure for period
Scottish Power	Reservoir level (m)	2001, 2004, 2007	**Daily** Max and Min
Scottish Power	Reservoir level (m)	2008, 2009, 2010, 2011	**Hourly**

Table 3.2: Cruachan reservoir level data sources, and benchmarks

Where the more recent (2008-2011), increased resolution (hourly interval) data allows, water level change over a period will be aggregated. This is a simple innovative parameter to compare with drawdown, to provide insight into the total extent of water level oscillations over a period that might not be picked up by drawdown alone (see **Figure 3.1**).

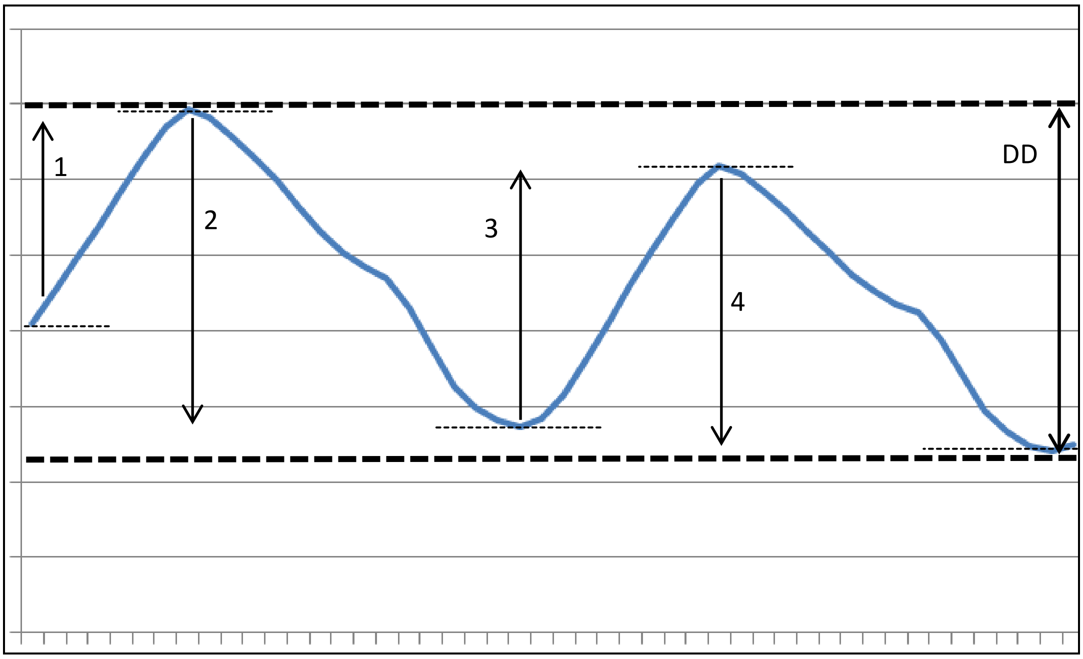


Figure 3.1: A comparison of how 'drawdown' (DD) and 'aggregated water level change' (Sum of 1-4) are calculated, on reservoir height, time graph

Secondly, parameters will be compared with the findings of Smith et al. (1987) outlined above, which are used as benchmarks. This approach offers a way to assess the ecological and regulatory implications through identifying a 'categorical' or direction of change (i.e. divergence or convergence) similar to King et al. (2008). Finally in part one, the more recent data (2008-11) with increased resolution (hourly) will be used to profile the short term (weekly and daily) water level variability.

Of the daily reservoir data set (2001-2007), a few years were unfortunately incomplete and so could not be relied upon for a robust investigation. Consequently only years 2001, 2004 and 2007 remain. In addition to providing the benchmarks, Smith et al. (1987) also referred to the annual average drawdown for 1975-80, which is also utilised for this investigation, as noted in **Table 3.2**

3.4.2 Linking Cruachan operation with the changing wider generation context

As a pumped storage scheme, Cruachan is run to support the efficiency of the grid, integrating generation with the national demand profile. Being largely a sealed hydrological system it is under little external influence, with reservoir variability tied principally to management decisions regarding generation. It has been suggested (Knudsen and Ruud, 2011), and shown in a similar scenario elsewhere (Wolfgang et al., 2009), that when the wider generation or demand context changes, operational changes are made to reflect this changing need. It is this premise that is applied to this case study of Cruachan.

Whilst it is not possible here to pinpoint specific thresholds of change in the generation mix, a review of the general trends in generation will inform an appraisal of the changing grid influences on Cruachan. Notably however, in the last few years, two of the four units at Cruachan have been contracted to the National Grid from 0730 to 2300hrs to 'spin in air' on standby, and to come quickly on-line to meet short term generational needs (B Wales, pers. comm 22 November 2012). Thus, the influence of the grid, specifically in the context of generation, has become more acute.

3.4.3 Limitations and justification

This research acknowledges two limiting factors in reference to the use of Cruachan as a case study, which will be touched upon here, but also addressed in more depth in the discussion. Firstly, as highlighted in the site description, the upper reservoir under consideration is artificial, created for the purposes of the scheme, raising questions regarding the degree to which its ecological needs should be considered against significant power generation benefits. Secondly, due to the operation of the pumped storage scheme, the magnitude (drawdown range) of water level change at Cruachan is often outside the tolerance thresholds of many aquatic species, potentially lessening its usefulness as a case study by which to examine change and the relationship between energy generation and ecological outcomes.

The underlying purpose of this research is to highlight and examine the linkages between energy and water disciplines, enabling an informed discussion regarding outcomes for future sustainable renewable generation. Given the above limitations, specifically the significant magnitude of drawdown at Cruachan, this methodology has put additional emphasis on the changing *profile* of reservoir variability, rather than the absolute values involved. In doing so the intention is to provide insight into how wider context and generation needs shape ecological outcomes, but in a way which can be seen as a template to consider at a wider policy level, or to apply to other sites undergoing similar changing influences.

Cruachan itself, as a pumped storage scheme, operates mostly as a 'sealed system' with variability in external hydrological influences (e.g. precipitation or runoff) not a significant factor in shaping the generational profile. Indeed, rather than regulatory constraints or climatic and local precipitation aspects being influential factors in shaping the generational approach as you would expect with most hydropower schemes, the most significant influence for Cruachan is the profile of external electricity demand needs (B Wales 2012, pers. comm 22 November).

For the purposes of this case study this characteristic allows the focus to remain on the influence of wider policy and energy generation drivers, with minimised compounding environmental variables. This study will not restrict the analysis of water level profile change to ecology present at Cruachan, but rather also consider species that may be present elsewhere at hydropower reservoirs in Scotland. Again, this is so the variability trends and their significance can be readily considered at other sites in Scotland, or to inform debate more widely regarding the regulation of water resources in a changing world.

Examining a changing water level profile through its convergence or divergence with a meaningfully limited number of ecological parameter benchmarks allows a categorical analysis of change (e.g. King et al., 2008). Such an approach seeks to overcome the uncertainties of trying to work with specific ecological thresholds, which will differ by site due to hydrological variability (Gilvear et al., 2001; Marsh and Anderson, 2001), and water regulation characteristics (Petts, 1984). Similarly, examining the shorter term daily or weekly water level profile and its significance for ecological needs provides a discernible mechanism to explore the relationship between peaking hydropower generation and ecological and regulatory challenges, now and into the future.

Enabling the efficient integration of other renewable technologies, peaking and pumped storage hydropower have a heightened role in supporting a low carbon generation mix, seen through the renewed consideration of the technology (Scottish Government 2010b) the recent 600MW Coire Glass proposal and the moves to increase the capacity of Cruachan. It is envisaged that through this research the changing historic and future reservoir characteristics, driven by a wider national context and shared energy needs profile, can be distilled down to a number of key findings and 'exported' to other peaking storage hydropower schemes in Scotland.

This output can inform assessments into the potential ecological challenges faced by schemes in the future, and will identify key pressures and 'pinch-points' for sustainable hydropower regulation at a scheme and national level. It will also enable further informed discussion about the future acceptability and management of storage hydropower schemes, given future energy needs, and potentially changing water level profiles.

PART ONE: Assessing the changing UK electricity generation mix (1966-2010)

3.5 ELECTRICITY GENERATION IN THE UK

The electricity generation sector in the UK is characterised by a reliance on a number of centralised, large scale thermal power stations linked to a national transmission grid. A fairly diverse technological generation mix has often supported energy resilience and helped to meet demand profile needs, over seasonal and daily timescales (DECC, 2007). In 2010, the top three contributors were natural gas (144KWh, 42%), coal (104KWh, 31%) and nuclear (66KWh, 19%) (National Grid, 2011).

3.5.1 Grid balancing and diversity

Electricity supply in the UK is facilitated by a distribution grid that works to ensure supply equals demand at minimised operation costs (both economic and environmental) to the system as a whole (IEA, 2005). Large national grids provide an opportunity to match deficits through spatial and technological diversity, whilst adding stability and predictability to generation and demand.

The composition of the UK generation grid becomes important due to the differences in output profile and 'capacity factors' between technologies, making over reliance on one technology problematic. A capacity factor of a power plant is an expression of the amount of electricity produced over a period, limited by operational, maintenance or environmental conditions, as a percentage of its theoretical maximum in line with its installed capacity. They therefore provide a way to consider how much electricity an installation or fleet of generators can produce over a period, and hints at their shorter term output profile or level of intermittency, which in turn presents implications for matching electricity supply to demand.

	2007	**2008**	**2009**	**2010**	**2011**	**5-yr Av**
Gas	64.7	71	64.2	61.6	47.8	**61.9**
Nuclear	59.6	49.4	65.6	59.3	66.4	**60.1**
Bioenergy*	52.7	52.4	54.9	53.5	43.1	**51.3**
Coal	46.7	45	38.5	40.2	40.8	**42.2**
Oil	44.6	39.3	33.2	34.5	34.7	**37.3**
Hydro**	38.2	37.4	36.7	25.4	39.1	**35.4**
Wind***	27.7	27.5	27.1	23.7	29.8	**27.2**
Photovoltaics	9.9	9.6	9.3	7.3	5.5	**8.3**

Table 3.3 UK average annual capacity factor (%) by technology (DUKES 2012)
(*Bioenergy varies by type, **not including pumped storage, *** onshore wind 5-yr av equals 26.2%, offshore av 28.2%)

As a comparison, **Table 3.3** shows that centralised thermal, fuel driven technologies have a higher capacity factor than renewable technologies that rely on certain environmental conditions. As an example, nuclear power stations in the UK commonly operate at a capacity factor of upwards of 50%, whereas the onshore wind five-year average is 26.2%, indicating a higher probability that wind will operate below its theoretical maximum at a given point in time. Technologies such as nuclear and coal with high load factors, in addition to historically having little operational flexibility before suffering efficiency losses, will often therefore generate a constant rate 'base-load', orientated towards a grid's continuous demand profile.

Grid elements such as Cruachan offer a way to balance actively the constituent technologies of the electricity grid, ensuring a more (demand) targeted delivery of base-load excess (i.e. from large thermal plants) and more intermittent technologies (i.e. wind). At its outset the Cruachan scheme specifically offered planned, targeted generation that complemented the output of these larger thermal and nuclear plants, such as the then proposed Hunterston 'A' station (Sidebotham and Kennedy, 1990).

3.5.2 A changing UK electricity generation mix

The historical development of the sector has brought a changing technological composition, presenting continuing challenges and uncertainties for delivering the most appropriate mix to meet medium and long term energy policy goals (DECC, 2007). The energy mix of the past 50 years has, in consequence, been shaped by the interplay and interaction of these different technologies, and the influence of external factors such as socio-economics, resource availability and energy policy.

The historical (1965-2011) trend in the composition of electricity generation in the UK is presented in TWh in **Figure 3.2**. In 1966 as Cruachan became operational, coal still formed over two-thirds of generation, supported by oil (16%) and nuclear (10%). Oil generation peaked in 1972 delivering 30% (78 TWh) of generation, apart from when it was relied upon to compensate for the 1984-85 coal miners' strike. Since then oil generation output has steadily fallen, from 9% (29 TWh) in 1989, to under 1% (2 TWh) in 2011.

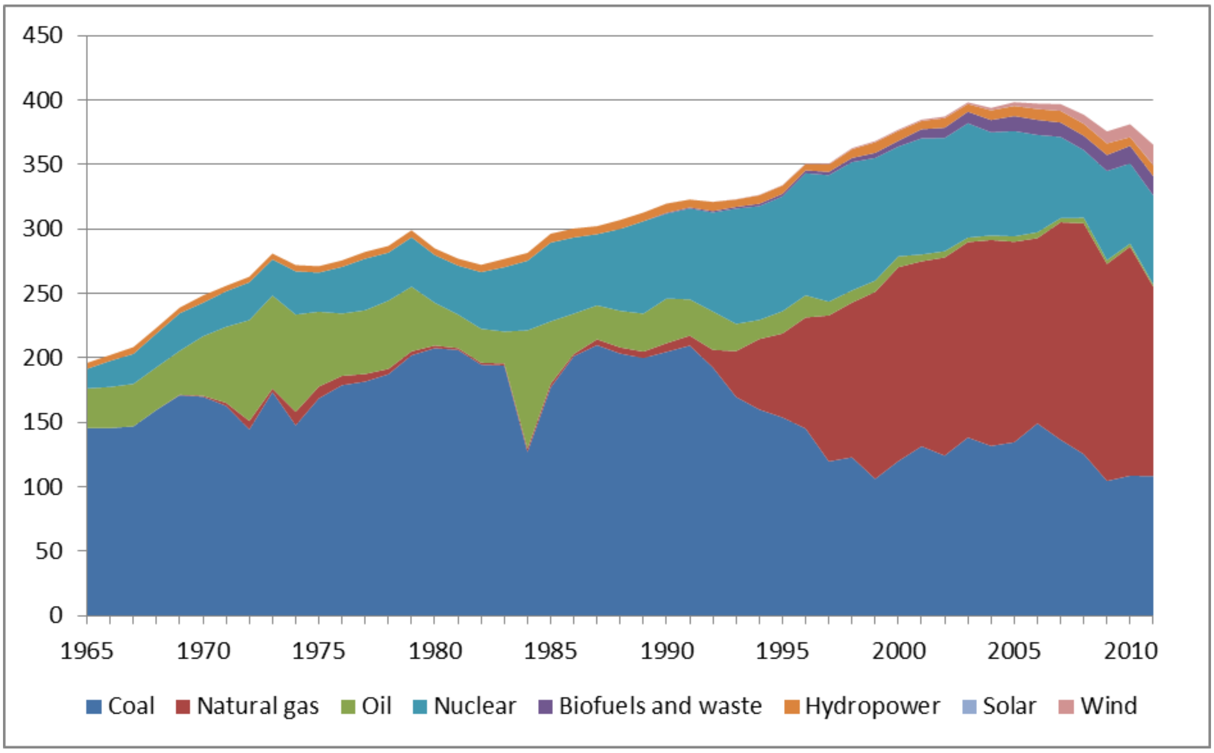


Figure 3.2: UK electricity generation by technology (1965-2011) (TWh) (Source: IEA, 2012)

The UK has a long history of nuclear generation dating back to the 1950s. Since then its contribution has grown steadily, from 10% (20 TWh) in 1966, to its peak in 1998 of 27% (99 TWh). More recently nuclear output has fluctuated due to site closures, and maintenance outages (DECC, 2012a).

After the 1989 privatisation, gas generation was no longer subject to EU restrictions. This change permitted the contribution in the UK mix to rise rapidly. This 'dash for gas' drove generation from a level of 2% (5 TWh) in 1989, to figures similar to 2008 of 179 TWh (46%).

The largest contributor throughout the 1970s and 1980s and early 1990s was provided by coal generation, with a proportional peak in 1981 of 74% (206 TWh). This fell after the increases in gas production and also in total-overall generation, but also halved in actual terms, down to 29% (108TWh) in 2010. Since 2000, coal generation has fluctuated, being called upon to make up shortfalls in nuclear and gas output due to maintenance outages and when gas prices became higher (DECC, 2012a).

3.5.3 The emergence of renewables in the UK and Scotland

Although large scale use of hydropower has existed in Scotland since the 1950s, the renewable era in the UK began in the early 1990s with the Non-Fossil Fuel Obligation (NFFO), and subsequent delivery mechanisms. Especially early on, the market led Renewables Obligation supported the established renewable technologies, leading to a lack of diversity in generation and a delay in the realisation of available resources (e.g. offshore wind) (Mitchell and Connor, 2004). **Figure 3.3** presents the composition of renewable electricity generation in the UK since 1990. The contribution of (mainly historic Scottish) hydropower to the renewables mix is fairly constant over the period, averaging 5 TWh a year. However, due to the growing penetration of other technologies hydropower, proportionally fell from 90% of renewable generation in 1990, to 21% in 2009.

Wind generation (mostly onshore) has emerged as the largest renewable contributor in the UK, with previously only around 9 GWh in 1990, rising to 10 TWh in 2010. Generation from biomass and landfill gas also increased over the period, but to a lesser extent. In 1990 biomass and landfill gas generated more than wind technology at 139 GWh and 457 GWh, rising to 7 TWh and 5 TWh respectively in 2010.

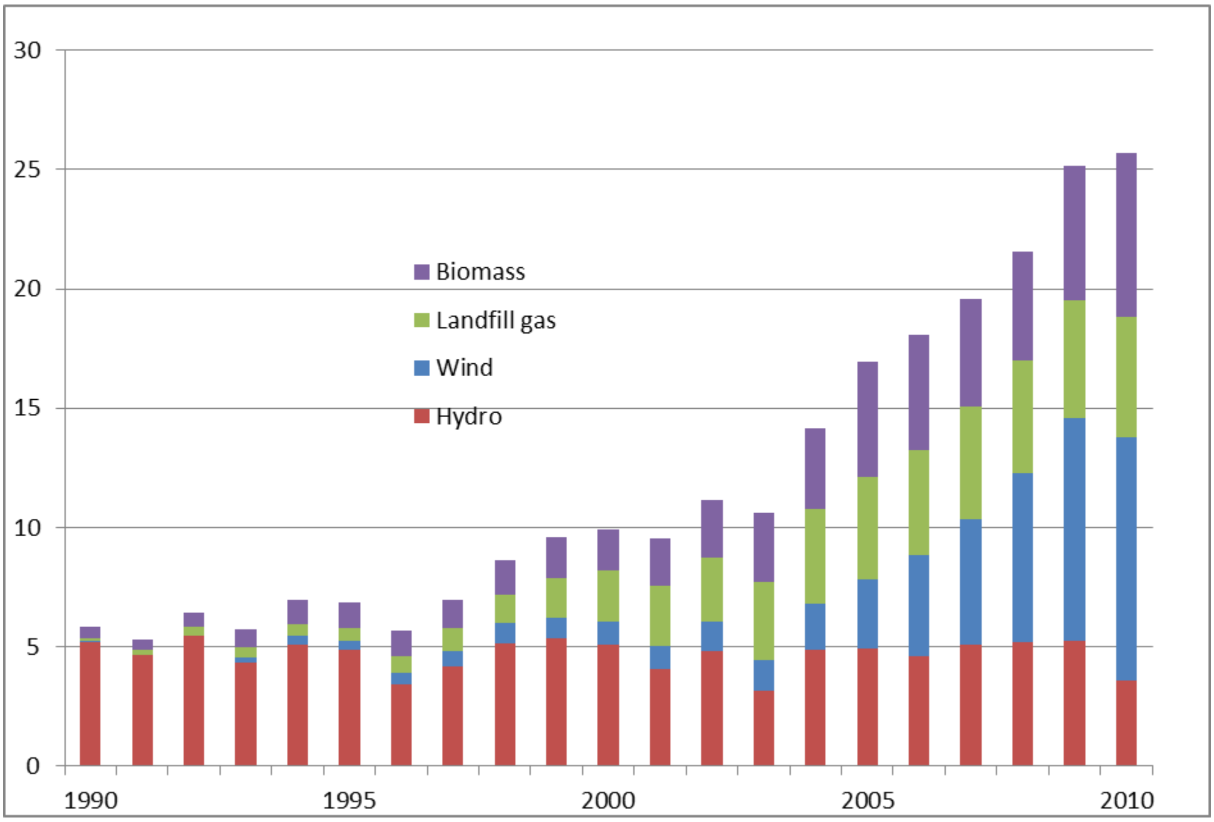


Figure 3.3: UK renewable electricity generated by technology (1990-2010) (TWh) (Source: DECC, 2012a**)**

Although of course contributing to the UK renewable portfolio, consideration of the Scottish renewables mix is important due to the generation proximity to Cruachan. **Figure 3.4** presents a similar development composition since 2000. While categorised with solar, a much smaller contributor, (onshore) wind energy has undergone a similar trajectory of increased penetration, accounting for only 217 GWh in 2000 rising to 4.8 TWh over 50% of generation in 2010. Scotland shows less renewable diversity to date, with hydropower and the growing wind proportion providing far greater amounts than any other technology.

These figures show that in 2010, the UK as a whole generated 3.6 TWh from hydropower, 3.2 TWh (88%) of which was provided by Scotland. By way of comparison, there was 10.1 TWh provided by UK wind power, with 4.8 TWh (47.5%) generated in Scotland. Finally, **Table 3.4** shows the 2010 contribution by all technologies, for Scotland and the UK, and the current penetration by wind. It highlights that renewables formed 6.8% (25.9 TWh) of electricity supply in the UK, and 19.4% (9.5 TWh) in Scotland. In 2011 UK wind generation rose to 15.75 TWh (4.5%), with total renewables accounting for 9.5% of all electricity supplied in the UK.

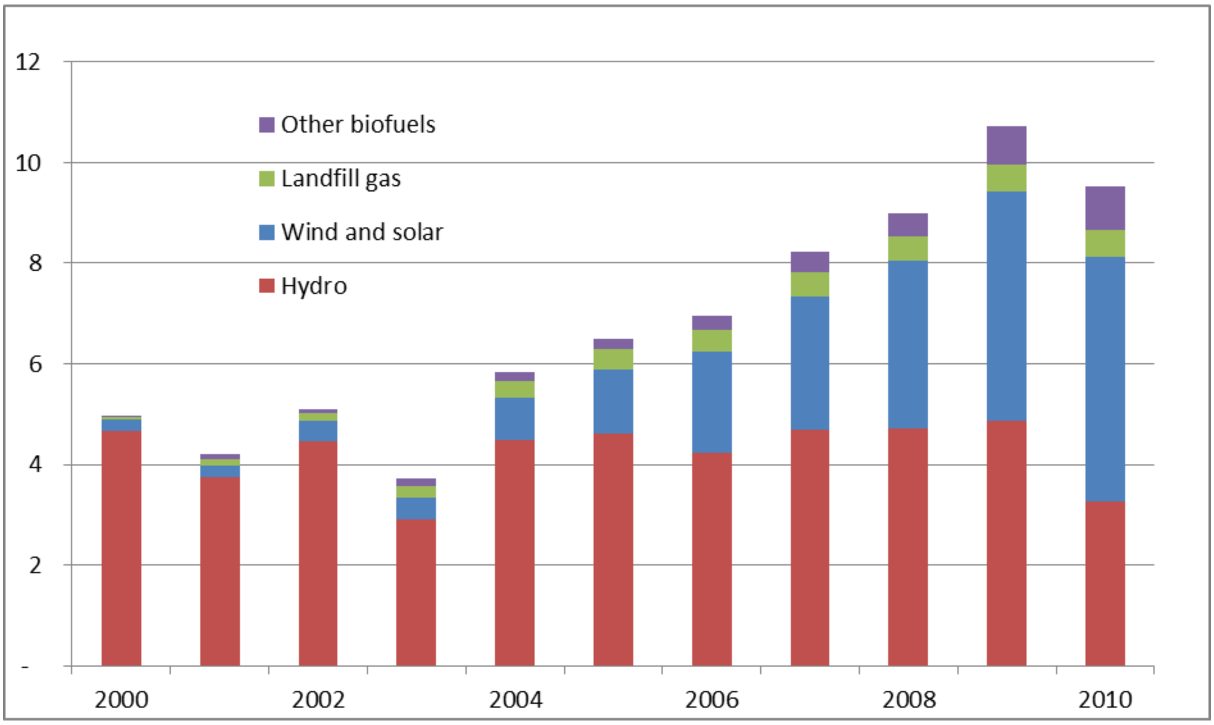


Figure 3.4: Renewable electricity generated by technology in Scotland (2000-2010) (TWh)

UK	**TWh**	**%**	**Scotland**	**TWh**	**%**
Coal	107.7	28.4	Coal	14.7	30.0
Gas	175.7	46.4	Gas	8.4	17.1
Nuclear	62.1	16.4	Nuclear	15.3	31.1
Oil	4.8	1.3	Oil	1.2	2.5
Hydro	3.6	1.0	Hydro	3.3	6.6
Wind	10.2	**2.7**	Wind, wave, tidal and solar	4.9	**9.9**
Other renewables	12.0	3.2	Landfill gas	0.5	1.1
Other fuels	2.5	0.7	Other biofuels	0.9	1.7
Total renewables	25.9	**6.8**	Total renewables	9.5	**19.4**
Total all	378.6		Total all	49.1	

Table 3.4: Electricity supplied in UK and Scotland (2010) by technology (DECC, 2012a; Scottish Government, 2012)

3.5.4 Wind intermittency and the grid

Renewables across all technologies are by their nature very much shaped and constrained by natural conditions, be it the potential available capacity at a national scale, or generation profile at a scheme level. It is this aspect that makes the integration of larger amounts of renewables an increasingly important issue for the management of electricity grids (IEA, 2005). With wind generation being tied to wind speed, there is a good degree of certainty regarding the output of a given wind turbine seasonally, annually, or over its lifetime. However it is the potential for unpredicted variations in wind speeds over short and diurnal periods, and in turn intermittent generation output, which can lead to problems with energy supply management (Albadi and El-Saadany, 2010).

Since its implementation the UK national grid has been balancing electricity supply from a range of generators against national demand needs. This balance is achieved either through active management, or through the inherent technological and geographic diversity of a given national generation mix (IEA, 2005). These approaches are also applied to the management of intermittent generation, where rather than ensure steady output from each generator, the grid seeks to ensure demand is met at minimised operation costs to the electricity system as a whole. However, as wind becomes an increasing proportion of generation, its intermittent generation profile, if divergent from demand, in addition to the resulting reduction in technological and spatial diversity of the wider electricity mix, presents increasing challenges for the reserve requirements of the network (Ilex, 2002; Mott Macdonald, 2003). One recent implication is the greater value being placed on existing storage capabilities that seek to match supply to demand, such as pumped-storage hydropower (Scottish Government, 2010b).

The National Grid manages the second-by-second real time balance between system demand and total generation, expressed by the concept of 'system frequency'. If demand is greater than generation, the system frequency falls, whereas if generation is greater than demand, the frequency rises. Following a demand or generation fault, the national grid allows for a certain level of system frequency deviation before it engages a Primary or Secondary response as an automatic increase in generation delivered in under 10 and 30 seconds respectively (National Grid, 2011). As wind becomes a greater proportion of the generation mix, a further application and perhaps capacity for frequency response is needed to manage electricity shortfalls, or reduced system frequency.

3.5.5 Working with wind generation

The variability in wind resource means wind power typically generates below the maximum rated output, and with a UK wide long term average capacity factor of 30% (Sinden, 2007) it is suggested this can lead to challenges for energy supply management (Albadi and El-Saadany, 2010). The profile of a given wind resource can be expressed through fluctuations in capacity factor over a range of timescales, conveying the reliability of wind power to contribute to an electricity network at a given time or over a period. Converting long term (1970-2003) wind resource monitoring data from a diversified sample of UK sites, Sinden (2007) profiled the UK wind resource availability through a changing UK average capacity factor over annual, monthly and hourly timeframes. As displayed in **Figure 3.5**, it was found:

- Around one-third of annual electricity production is provided in December, January and February alone (CF values between 37% and 40%).

- The months of June, July and August account for only 17% of annual electricity production (CF values between 20% and 22%)

- The UK wind resource displays a clear pattern of increased wind power output in daylight hours across all seasons, with this diurnal comparison most pronounced in summer months.

- Winter presents the smallest variability in capacity factor between day and night, but its overall wind power output is greater than the other three seasons, when comparing between times of the day like for like.

- In addition, although the long-term average annual capacity factor is 30%, variability exists between years' wind power availability, including more significant fluctuations such as from 1986 (CF 34%) to 1987 (CF 24%).

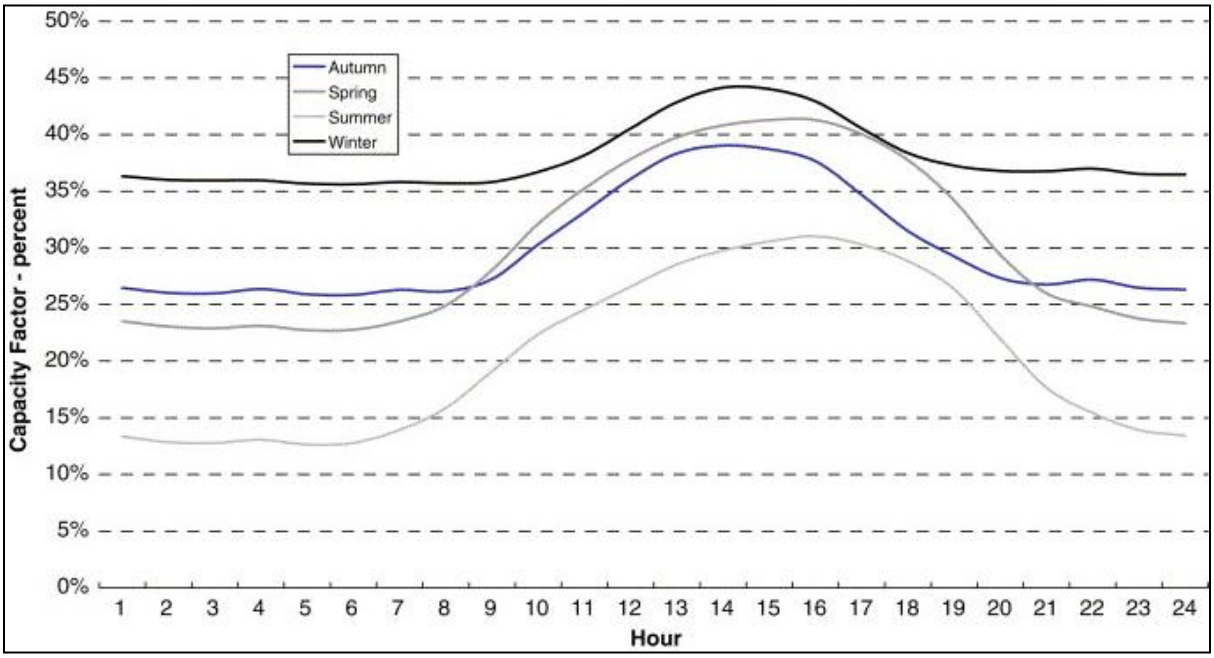


Figure 3.5: Average hourly wind power variability (capacity factor) by season (1970-2003 mean) (Sinden, 2007)

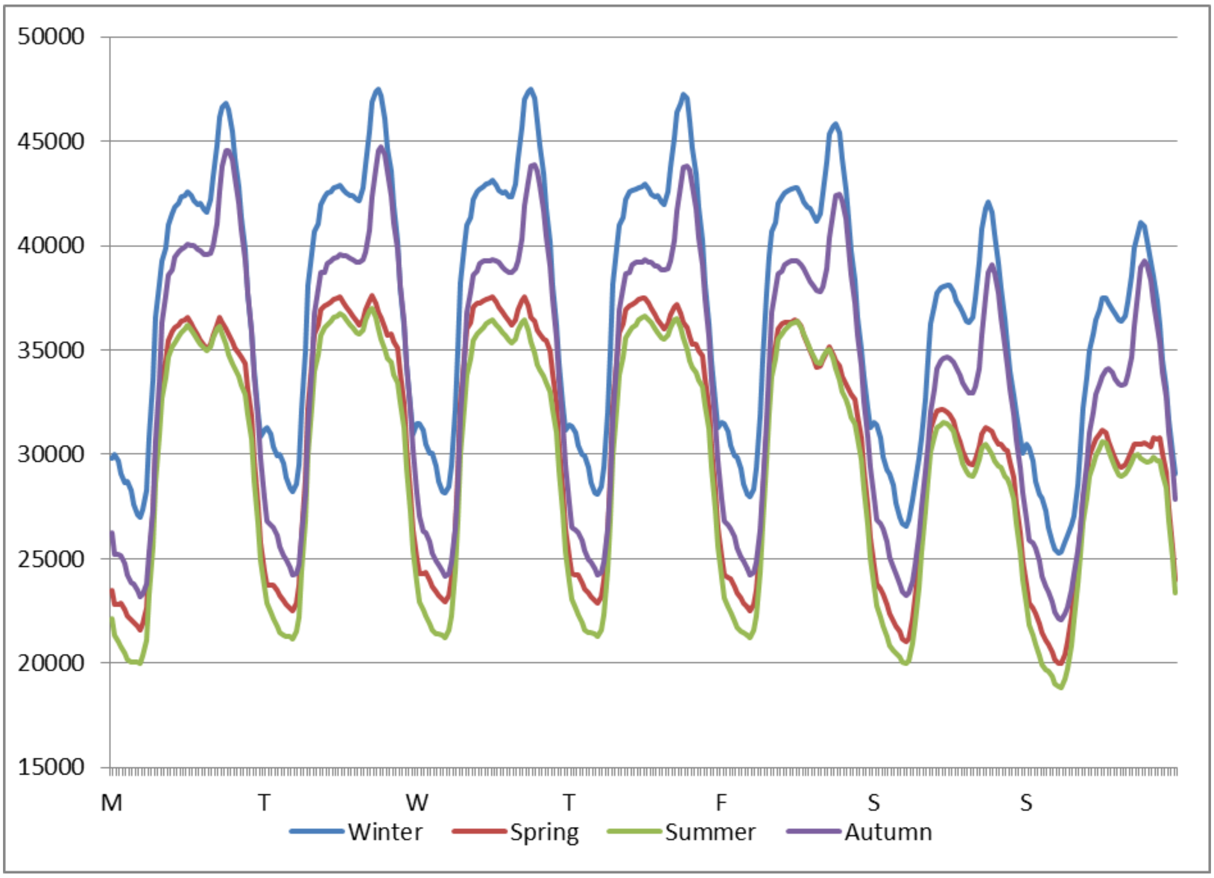


Figure 3.6: UK electricity weekly demand profile (MW), by season (2011) (National Grid, 2012)

This consideration of UK wind power profile through a diversified sample of sites presents insight into the seasonal and daily characteristics of wind generation. However, it is ultimately the relationship between the profiles of wind power output and electricity demand that is of greatest interest for electricity network integration (Sinden, 2007).

Calculated using half-hourly demand data from the National Grid, **Figure 3.6** presents a seasonal breakdown of the weekly and daily electricity national demand profile in the UK. Its average weekly profile shows an increasing load during the day with lunchtime and evening peaks, and lower demand at the weekend. There is however a distinct seasonality to the demand profile, with both peak and off-peak demand being higher in winter and autumn, over spring and summer equivalents.

Similar to the more in-depth analysis and outcomes provided by Sinden (2007), the temporal demand variability presented in **Figure 3.6** coincides broadly with the UK wind output variability in

Figure 3.5. This relationship is set out in **Table 3.5**, highlighting the positive association between output and demand characteristics, and is presented alongside the resulting implications for the electricity network and potential balancing elements such as Cruachan.

Sinden (2007) also investigates the potential for extreme (prohibitively low) wind events to disrupt wind generation over a significant spatial extent of the UK, and so affect national electricity supply. It was found low wind events (below a common generation thresholds of 4 ms^{-1}) that affect more than 20% of the UK, occur 60% of all hours on average. Similarly, low wind events that affect more than 50% of the UK occurs on average less than 10% of all hours. And finally, low wind events affecting more than 90% of the UK have an average recurrence rate of one hour per year. As such, the risk of wind outages across a high percentage of the land area of the UK for longer periods is extremely low.

Wind resource output profile (Figure 5.4)	**Grid demand profile** (Figure 5.5)	**Electricity Network and pumped storage implications**
Increased output in daylight hours	Demand load peaks during the day and early evening	Factors coincide, leaving theoretical reduced need for balancing mechanisms
Greatest seasonal output in winter months (Dec, Jan, Feb)	Highest demand in winter and autumn months	Factors coincide, leaving theoretical reduced need for balancing mechanisms
Lowest seasonal output in summer months (June, July, August)	Lowest demand in winter and spring months	Factors coincide, leaving theoretical reduced need for balancing mechanisms
Highest night time generation output occurs in Winter months	Highest night time (off-peak) demand in winter months	Factors coincide, leaving theoretical reduced need for balancing mechanisms

Table 3.5: A comparison of wind generation and network demand general characteristics

From the brief assessment here and through the work of Sinden (2007) we have seen that the average UK daily, weekly and seasonal wind generation output peaks generally coincide with the demand profile of the UK electricity network. As a result we are less likely to have low wind speed events during periods of high demand. Similarly, and only touched upon briefly here, given perceptions regarding the risk of intermittency and the threat of large-scale outages (e.g. Laughton, 2002; Sharman, 2005), low wind speed events have been shown (Sinden, 2007) to have only a limited impact in the UK, with the occurrence of outages that are shared across a significant proportion of the UK being limited to only relatively short periods of time through the year.

3.5.6 Electricity mix results summary and discussion

3.5.6.1 Changing generation and the advent of wind power

This examination of the changing electricity generation mix in the UK has highlighted the changing composition but continued dominance of large thermal, traditional base-load technologies over the last fifty years. From around 2003 in both the UK generally and Scotland in particular, the contribution from wind power grew significantly. In 2010 it formed 2.7% (10.2 TWh) of all generation in the UK, and about 9.9% (4.9 TWh) in Scotland.

With the traditional inherent inflexibility of large base load stations, and the growing penetration of potentially intermittent wind generation, questions have been raised regarding the challenges and implications for the integration of rising amounts of wind contribution in the electricity networks of the UK and other countries (e.g. Laughton, 2002; Sharman, 2005; Albadi and El-Saadany, 2010). However, the outcomes from Sinden (2007) considered and applied against the network demand profile presented here, have shown that the profile of national wind generation output generally coincides with the UK demand profile. Namely, over a daily and seasonal scale, wind output peaks correspond with demand periods (i.e. in daylight hours and in winter months), and similarly when there is typically lower output, this occurs at relatively lower demand periods (i.e. overnight and in the summer months). In addition, Sinden (2007) finds that extreme (low) wind events that affect a significant proportion of the UK, and thus that may undermine output from the national wind fleet, only occur for a very short period of time out of the whole year, and are therefore very low risk. With an increasing contribution of wind generation also occurring on a wider European scale, a similar challenge is occurring in Norway, as it evaluates how its large storage capacity can act as a storage battery to integrate the output of potentially intermittent renewable technologies (Solvang et al., 2012).

3.5.6.2 Considering the implications for pumped storage operation

In view of this general convergence of wind output and wider demand profiles, we can see how this dynamic would in theory not lead to an overt, additional pressure on Cruachan and other grid balancing elements. For example, in an alternative scenario where wind output instead peaked at night, divergent from demand, then as wind became an increasing proportion of the generation mix there would be a trend towards a greater need for diurnal balancing. Similarly, if the UK had a different seasonal electricity demand profile, with an additional, summer demand peak, as is common in Mediterranean climates that rely on air conditioning (Psiloglou et al., 2009), this again would not be well suited to the delivery profile tendencies of wind power in the UK, leading to a reduced efficiency of the wider network.

This discussed dynamic presents a positive picture regarding the effective integration of increasing amounts of wind power into the UK electricity network. However, as we have seen, due to the fact that short term electricity demand is not constant (National Grid, 2012), and that wind power output fluctuates over a shorter term (IEA, 2005) and is not ‘programmable’ to needs, there is still a requirement for the output of wind power often to be integrated through balancing elements.

The key aspect to this research is to examine how these wider generation trends affect the nature and profile of grid balancing elements, namely Cruachan, its operational profile, reservoir variability, and resulting regulatory challenges. Historically, network balancing approaches such as that taken with Cruachan seek to target demand periods, and so generate at a small number of predetermined peak times during the day (Sidebotham and Kennedy, 1990). This in turn shaped the original operational and reservoir handling profile at Cruachan, with long standardised drawdown periods during the day, and reservoir recharge at night (Parry and Henderson, 1991). This approach to balancing has traditionally been orientated towards a focus on standardised peak demand periods, rather than being generation led. It is conceivable however that given the increasing penetration of intermittent, with more erratic short-term generation profiles we could see a shift where balancing measures are increasingly led by generation output and shortfalls – and as a result transition to operate with less standardised profiles and increasing flexibility to compensate for shorter-term variability.

We have seen here that there is a general alignment of national wind generation profile (Figure 3.5) and UK demand needs (Figure 3.6). As set out in Table 3.5, this suggest that a growing proportional wind contribution, due to its increasing deployment (DECC, 2012a) and changes in the wider mix (National Grid, 2011), will mean that flexible grid capacity such as gas generators and active targeted elements such as Cruachan will have more of a filling in role, 'fine-tuning' output to demand, rather than a large seasonal and diurnal balancing role.

Moving forward, as this wider energy context and the interplay of wind generation and demand needs continues, Cruachan's value to the grid is increasing (Scottish Government, 2010b). However, two distinct potential outcomes result from this context. These are that firstly, Cruachan shifts towards more of a 'filling-in' type generational approach described above, but also secondly, that additional *generational* capacity and additional reservoir *storage* capacity from pumped storage will be of value to the grid.

These second two points can be seen as drivers underpinning the 600MW Coire Glass pumped storage scheme proposal, and more recent scoping work around extending Cruachan from 440 MW to 1040 MW (Scottish Government, 2014). Both these developments offer additional (reservoir) storage capacity, but also generational (installed) capacity. It is argued here therefore that whilst the wider energy context is creating specific changing generational demands upon Cruachan, this is set against an increasing need for storage and generational capacity to support grid balancing.

This research into the environmental implications of changing reservoir variability at Cruachan is predicated on engaging with the range and frequency of water level change, and how this deviates from natural conditions, as has been suggested in literature (e.g. SNH, 2010). Understanding and working with uncertainty is key to providing robust, meaningful research into change in the water environment (Werritty, 2002; Arthington et al., 2006; Acreman et al., 2009). For example, scientific understanding is often unable to predict specific reach level ecological outcomes from hydrological changes due to the multitude of factors and variables in a natural water system (Gilvear et al., 2001; Marsh and Anderson, 2001).

This research seeks to overcome this limit to knowledge that prevents detailed micro level outcomes to be predicted, by identifying the *categorical* change of ecologically significant parameters (Bragg et al., 2003), considering seasonal species sensitivities (SNIFFER, 2006), against known threshold conditions (Smith et al., 1987) taken as benchmarks. This assessment of the categorical direction of change (e.g. King et al., 2003) alongside a simple BBM type approach (King et al., 2008) that engages with ecological 'needs', which UK regulatory science is set to use more frequently (UKTAG, 2013), means that evidence showing there has been a transition of previously extreme conditions towards benchmarks can be used to conclude that this offers the potential for an improvement in conditions and littoral zone ecology.

PART TWO: Investigating water level and operational variability at Cruachan (1966-2010)

3.6 EXAMINING DRAWDOWN PARAMETERS

3.6.1 Annual, weekly and daily drawdown

The obtained data set allows for an analysis of the changing water level profile at Cruachan, examining various parameters over a number of years. **Figure 3.7** presents a comparison of *annual* drawdown (extent of change, difference between highest and lowest values) between the available years. It shows that despite some fluctuations, there is no clear trend at this scale

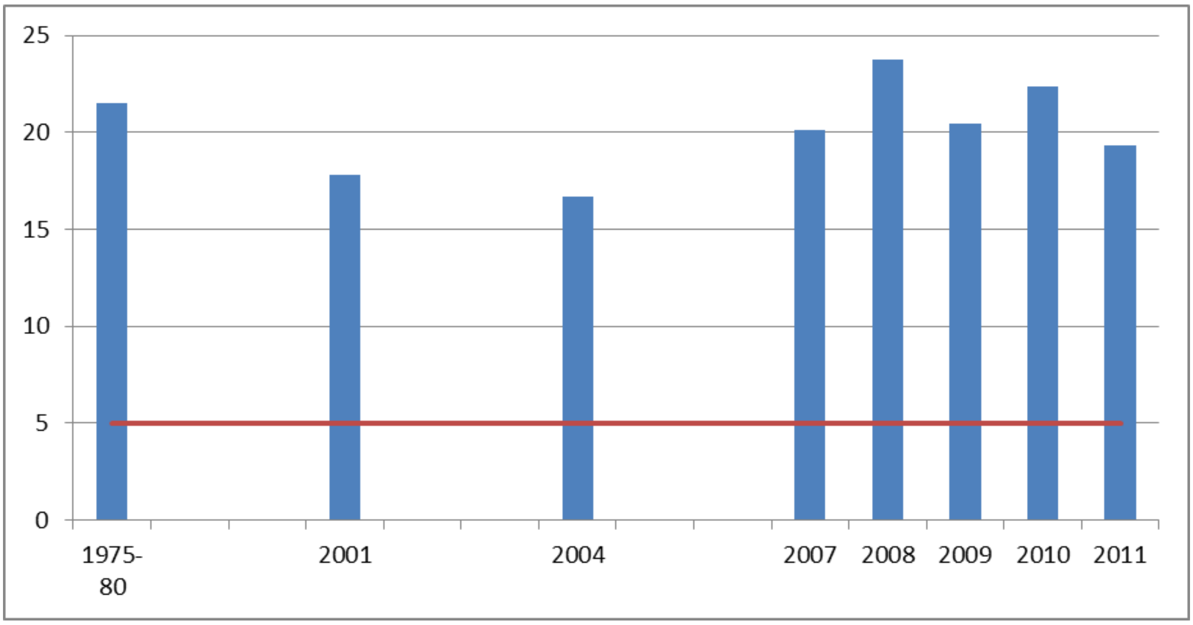


Figure 3.7: Cruachan Reservoir Annual Drawdown (m), by year, with benchmark

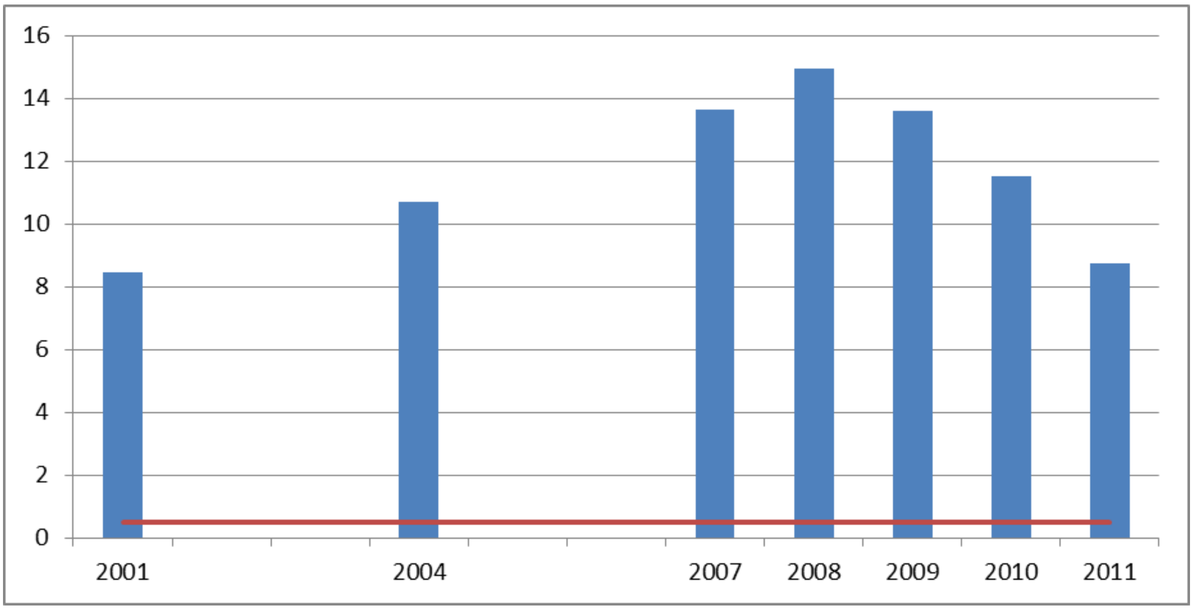


Figure 3.8: Cruachan Reservoir Mean Weekly Drawdown (m), by year, with benchmark

As such, there is no change in profile against the first Smith et al. (1987) benchmark of 5m annual drawdown.

Shifting towards a shorter timescale parameter, **Figure 3.8** presents a comparison of mean *weekly* drawdown for each year. At this scale a trend exists where drawdown peaked in 2007 and 2008 at over 13m, and then decreased for years 2010 and 2011, similar to 2001 levels. This recent decrease in mean weekly drawdown is a trend that brings it towards the second Smith et al. (1987) benchmark of 0.5m drawdown per week. Presenting mean *daily* drawdown, **Figure 3.9** displays a similar trend for a rise from 2001 levels, to a peak in 2007 and 2008 of around 8m per day, then a drop over years 2009 to 2011.

As the 2008-2011 data set provides increased resolution with hourly data points, an additional axis in **Figure 3.9** also displays average daily 'aggregated water level change' for that period. Whilst of a higher magnitude than drawdown due to capturing all fluctuations in water level within the drawdown extent of a time period, it also displays a trend of decrease from 2008 to 2011.

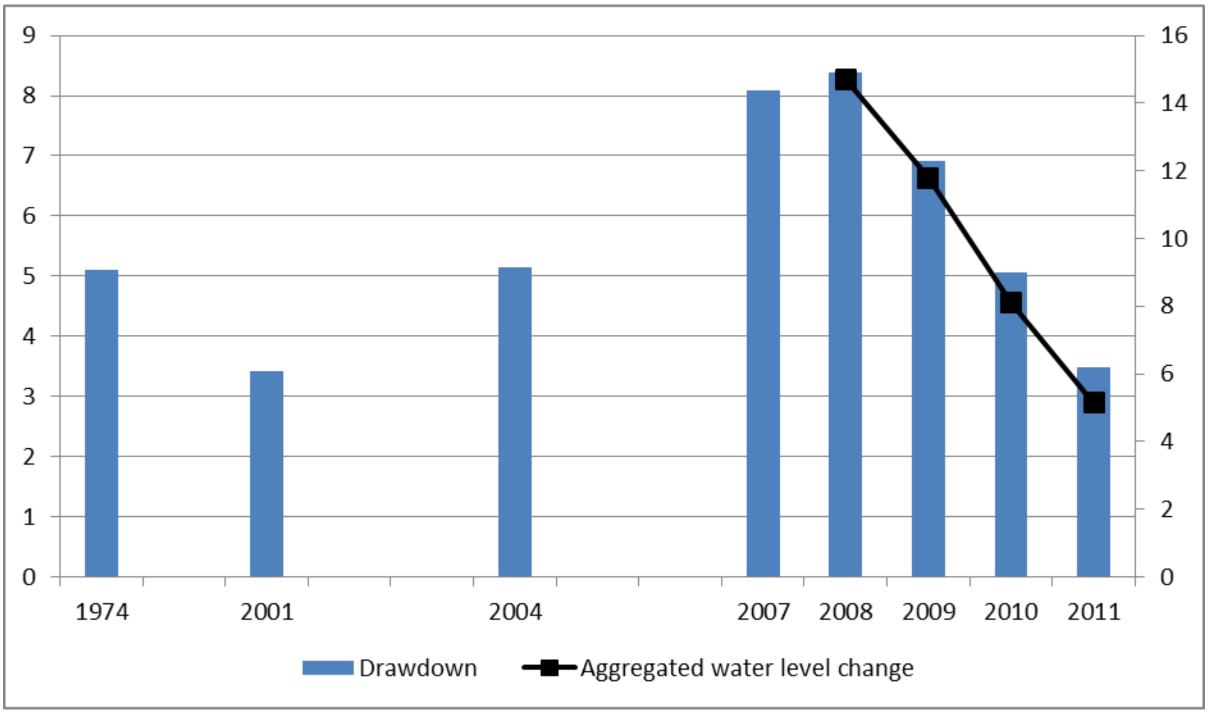


Figure 3.9: Cruachan Reservoir Mean Daily Drawdown, and aggregated daily mean water level change (m), by year

3.6.2 Seasonal drawdown

Figure 3.10 takes the mean weekly drawdown data presented in **Figure 3.8** and adds a seasonal dimension, displaying the weekly average per calendar month. Although somewhat of a variable picture, there does seem to be more disparity between years over the summer months, with the years with the lowest average weekly drawdown (2001 and 2011) moving towards the Smith et al (1987) benchmark ('BM') of 0.5m drawdown per week.

Given this transition to reduced shorter-term drawdown from 2008-2011, **Figure 3.11** takes the mean daily drawdown for that period and presents it in terms of day of the week. It shows that in addition to the actual drawdown falling from 2008-2011 (as per **Figure 3.9**), compared to 2008, later years have less of a weekly pattern, moving away from the tendency for a lower drawdown on Saturdays and Sundays.

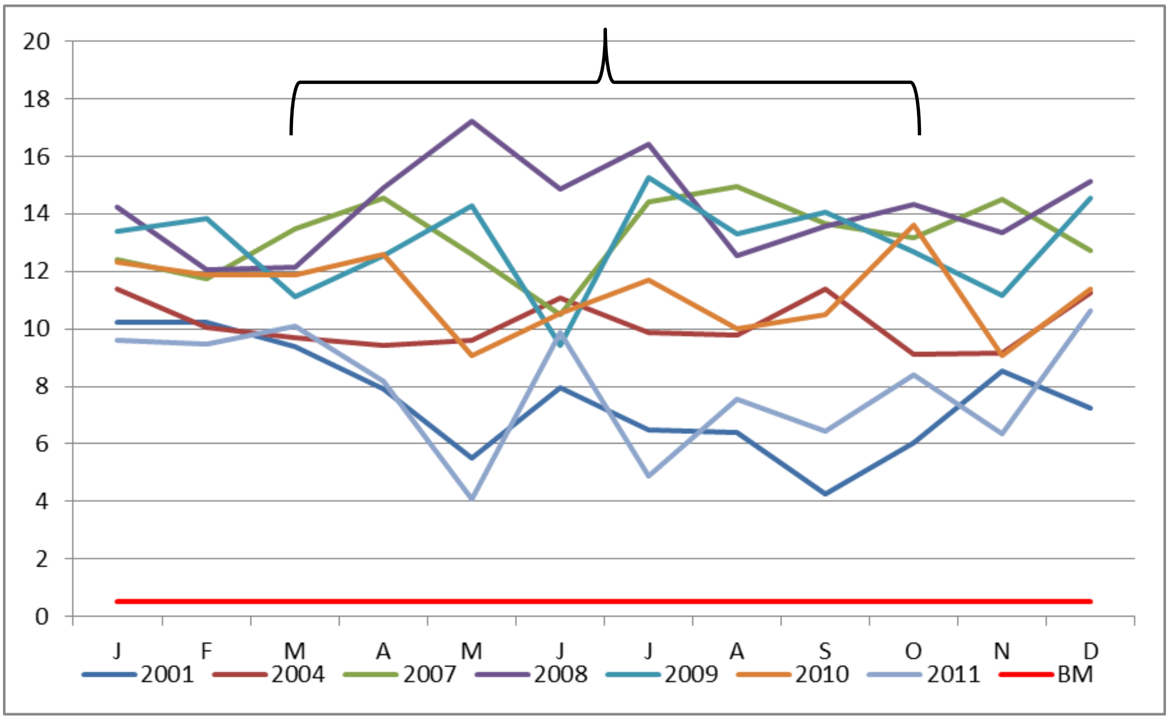


Figure 3.10 Average weekly drawdown (m), per month, by year, with benchmark

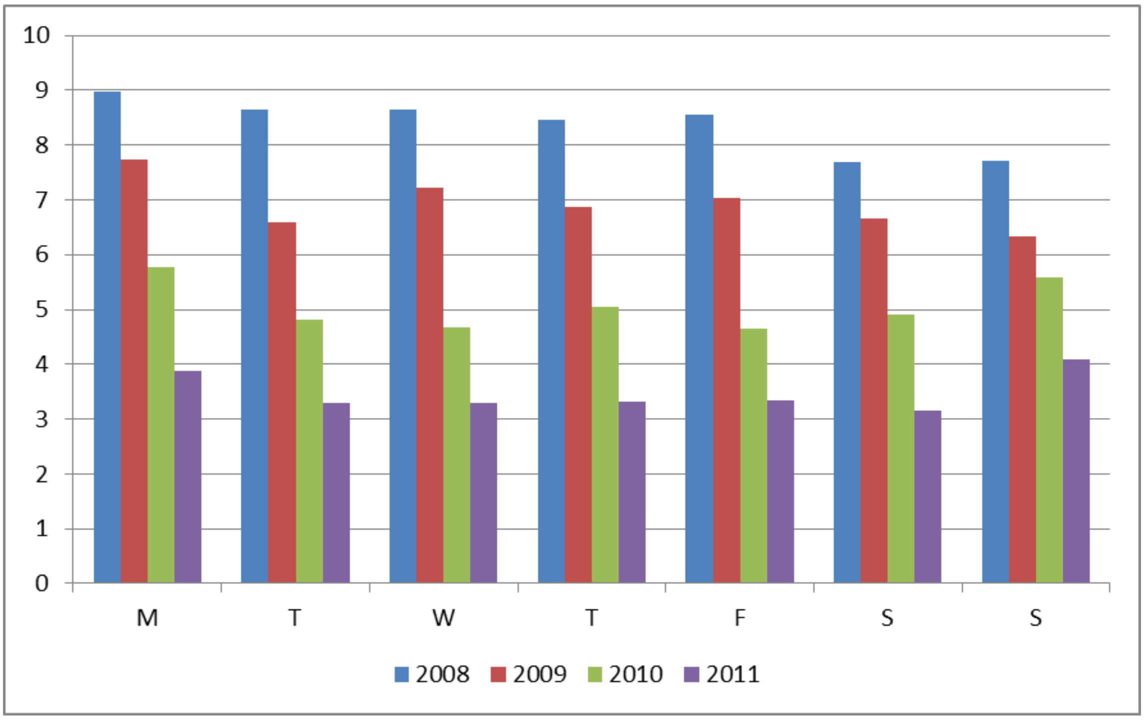
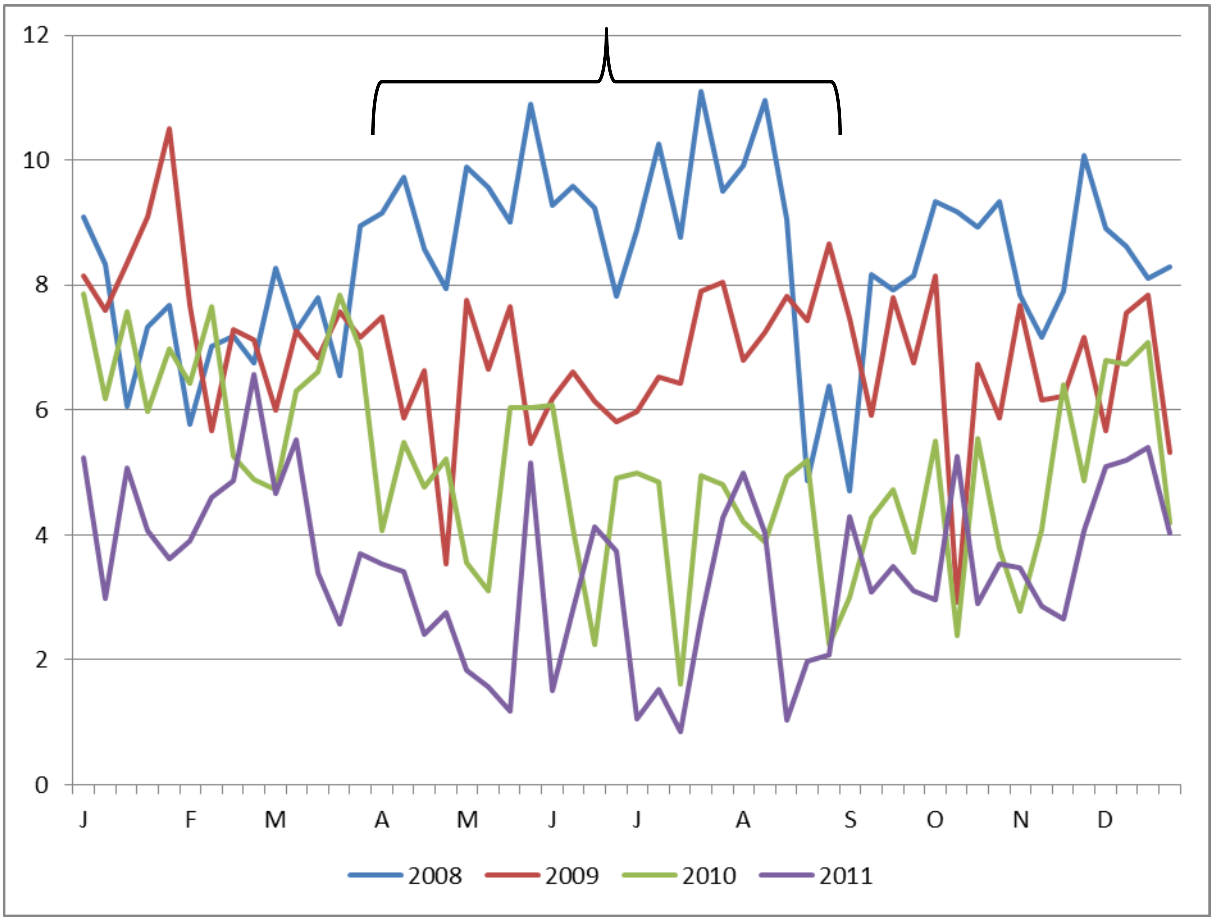


Figure 3.11 Mean daily drawdown (m), by day of the week and year

Taking *daily* drawdown for 2008-2011, averaged over each week of the year, **Figure 3.12** provides an indication of the seasonality changes in drawdown for the period. Illustrated by the brace, the distribution across each overlaid year indicates a greater disparity in drawdown between 2008 and 2011 in the summer months. So, in addition to the transition for reduced daily drawdown over the period (**Figure 3.9**), here we see this change is accentuated further between the months of March and September. Notably this additional seasonality towards less severe daily drawdown conditions occurs in a period of high ecological importance to species' annual life cycles (see **Table 3.1**).



3.12: Mean daily drawdown (m) per week, overlaid by year (2008-2011)

Given the transi for a reduced mean daily drawdown over 2008 to 2011, **Figure 3.13** presents the standard deviation of each figure for day of the week, so as to query the variability around these averages. It shows that that variability remains of a consistent magnitude across the years, but due to the downward drawdown trend, it rises proportionately.

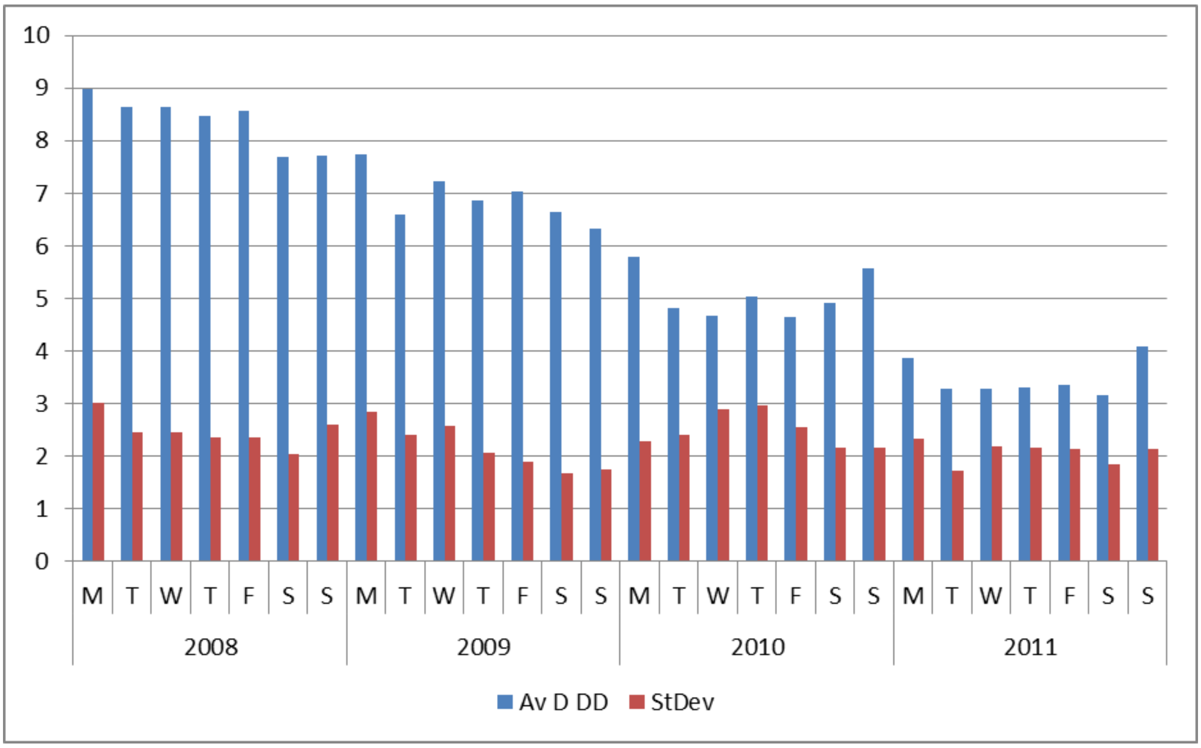


Figure 3.13 Mean Daily drawdown (m) by day of the week and year, with StDev

3.7 EXAMINING WATER LEVEL PROFILES AND VARIABILITY

3.7.1 Water level duration curves

A water level duration curve (WLDC) ranks the reservoir depth data and presents it as the percentage of time that any given level has been equalled or exceeded, allowing insight into the variability over the period. The **Figure 3.14** WLDC (2008-2011) for Cruachan presents a degree of uniformity between the years, but 2008 and 2009 display a steeper curve indicating a more variable and changing water level over 2010 and 2011, which are flatter, therefore more moderate in their variability profile. Q-values also vary between the years, with the Q90 in 2011 being higher at around 388m, and the Q10 in 2010 lowest at 394m. This suggests that low reservoir levels in 2011 were higher than in other years, and higher reservoir levels were lower in 2010 than in other years.

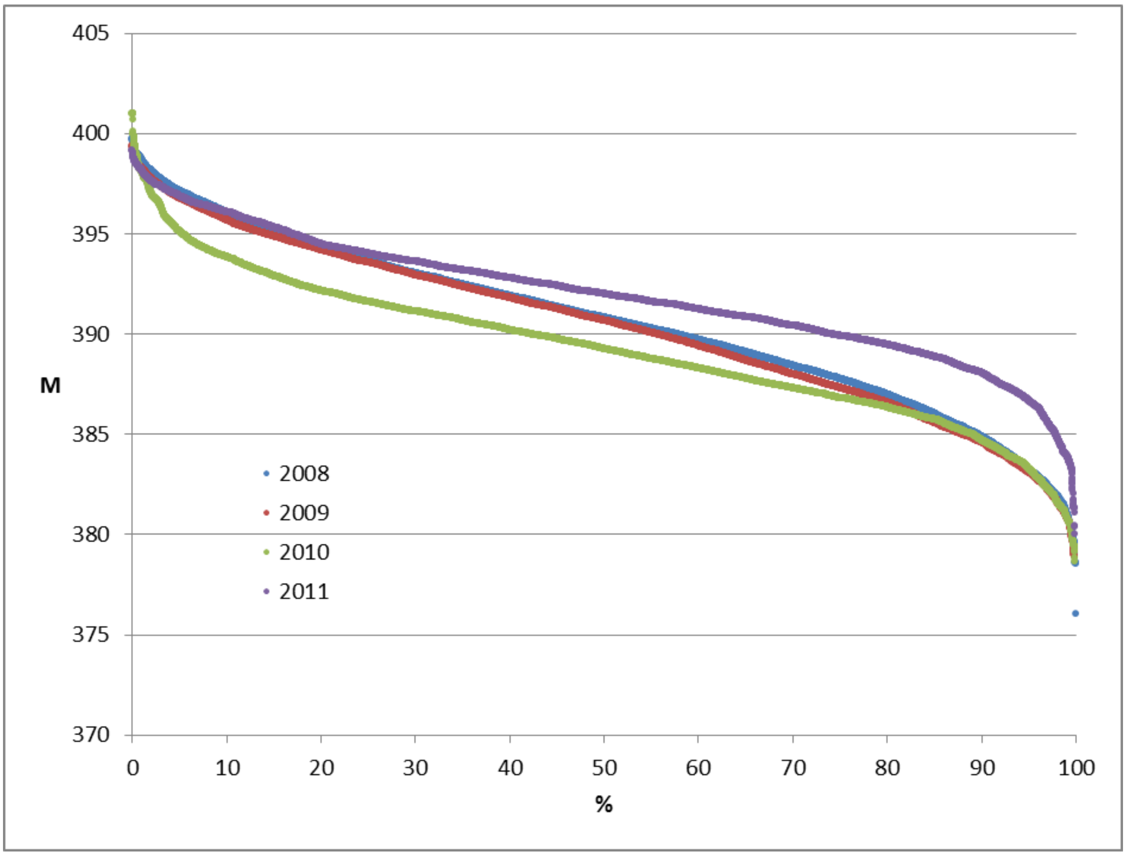


Figure 3.14: Annual Water Level (m) Duration Curve (2008-2011)

3.7.2 Comparing weekly profiles

The original approach to reservoir handling following construction in 1966 is provided in **Figure 3.15**.Presented as reservoir storage percentage, rather than metres (above sea level) depth, it depicts what has been described previously; that of diurnal variation with pumping at night and (although not distinguished here, typically two periods of) generation in the day, set against a weekly profile of incremental drawdown and reservoir recharge on the weekend.

Figure 3.16 displays the average weekly reservoir profile for Cruachan from 2008 to 2011. In comparison to the historical profile (**Figure 3.15)**, years 2008 and 2009 of **Figure 3.16** exhibit a similar average profile, with incremental weekly decrease then recharge at the weekend, overlaid by periods of significant standardised daily drawdown. Unlike the albeit the more pictorially presented historical profile, **Figure 3.16** shows that there is generation on the weekend, but with a reduced magnitude of drawdown and increased periods of inactivity, over weekday equivalents.

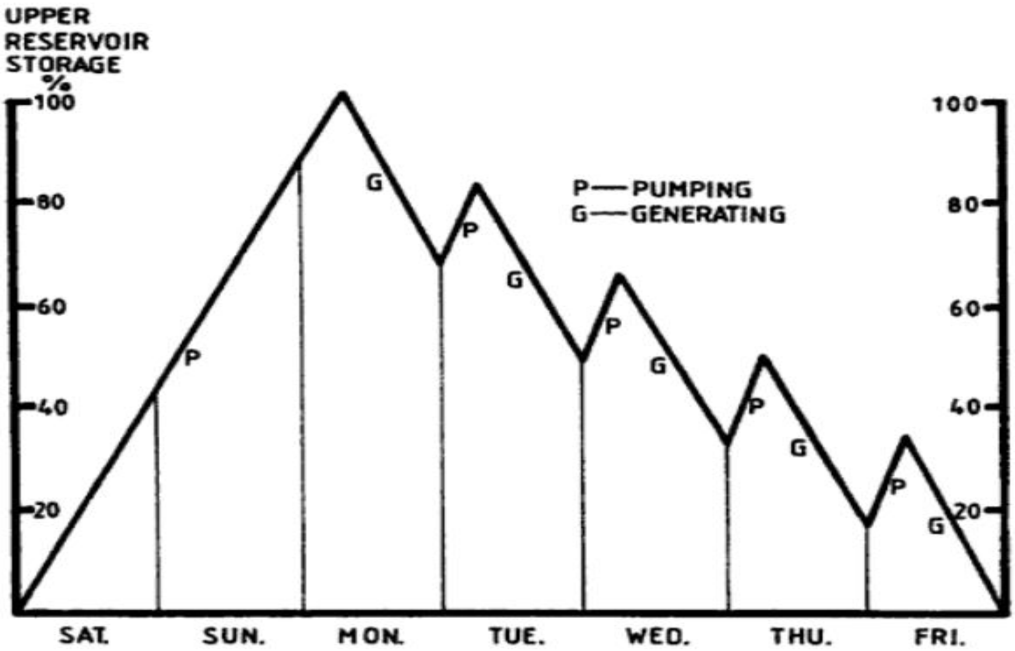


Figure 3.15: Cruachan reservoir original operational cycle (Sidebotham and Kennedy, 1990)

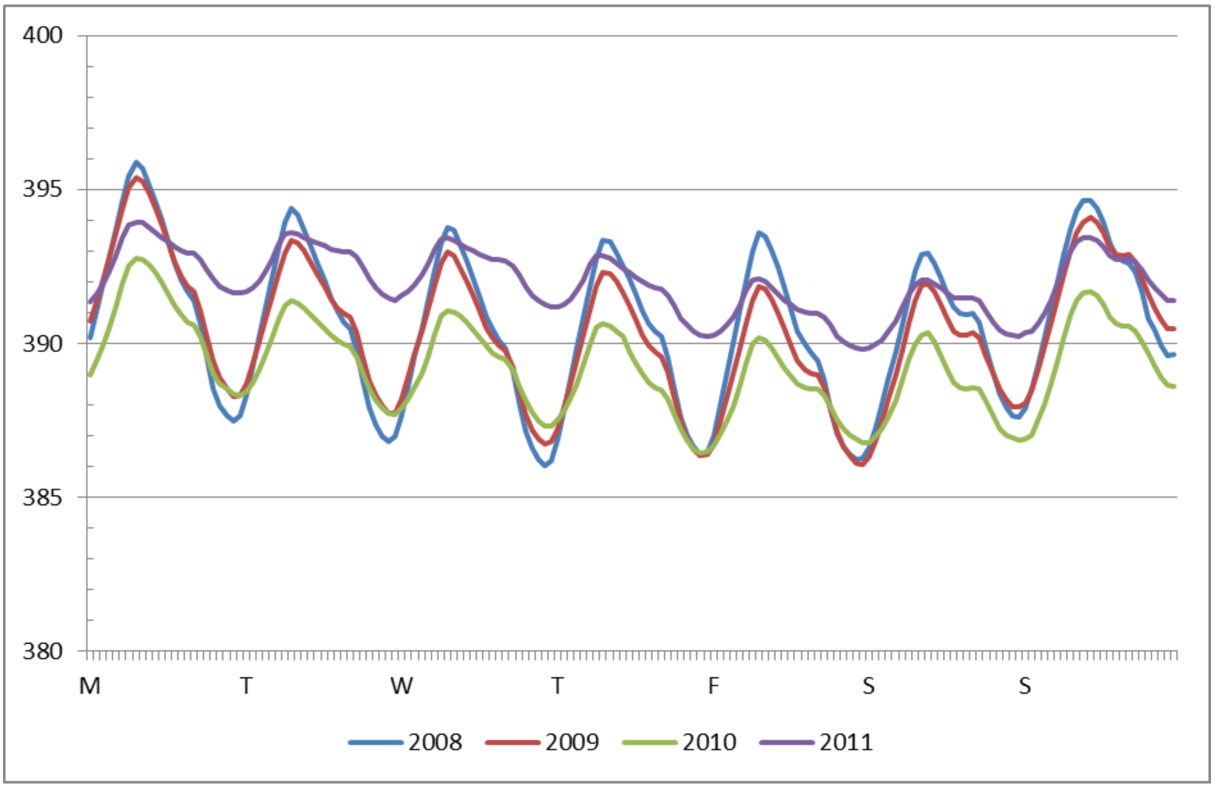


Figure 3.16: Mean weekly reservoir profile (m) (2008-2011)

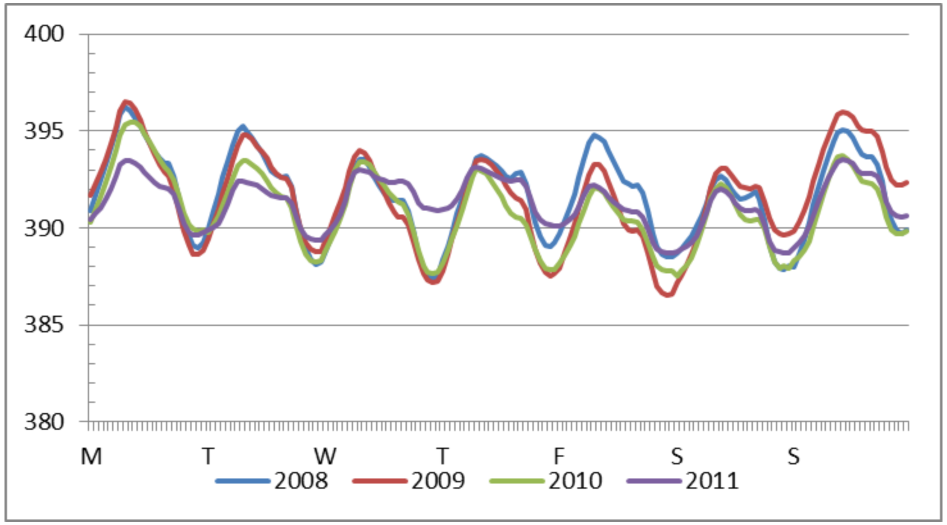
The difference between the years 2008 and 2009 that exhibit similar reservoir and thus operational characteristics to the historical model (**Figure 3.15**), and the subsequent years of 2010 and 2011, is also very apparent from **Figure 3.16**. As found previously, average daily drawdown decreases over the period 2008-2011. Here we see that the profiles of 2010, and to a greater extent, 2011, are visibly much more moderated, 'shallower' and less extreme in profile over 2008 and 2009. They still, however, display the timing and weekly and diurnal patterns found previously. These shallower variability profiles, driven by reduced daily drawdown, convey a 'slower' profile to the fluctuations, with water level change on average being less extreme in extent and speed.

From **Figure 3.16**, it is evident that 2010 visibly operates at a lower daily reservoir level than 2011, or indeed 2008 and 2009. A pattern exists however where although 2011 has reduced drawdown, its daily (average) water level *peaks* tend to align with 2008 and 2009 in terms of timing and extent. However, in contrast, 2010 tends to correspond with the lowest values (troughs) and timing of 2008 and 2009, which combined with 2010 displaying reduced daily average drawdown over those years, means that 2010 operates at a lower level on average.

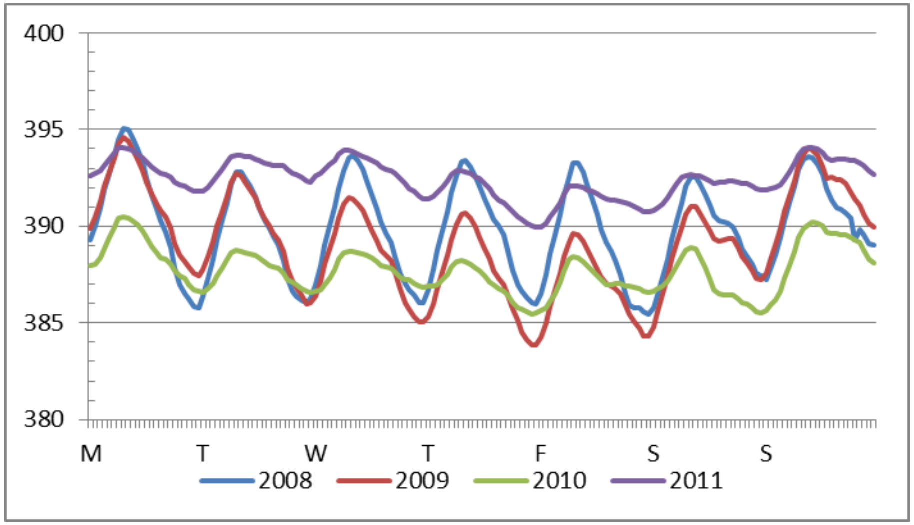
3.7.3 Seasonal aspects of water level profiles

3.7.3.1 Comparing seasonality between years

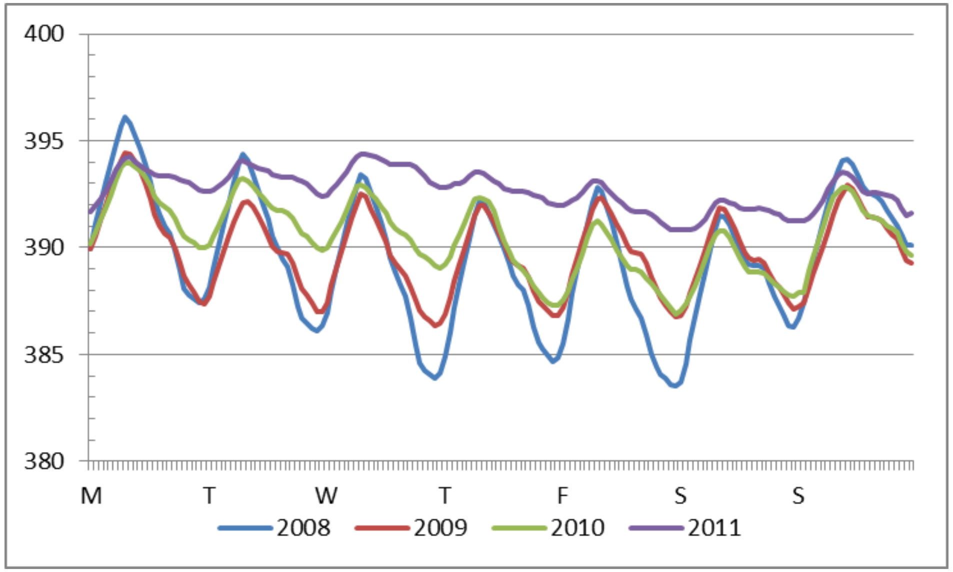
Taking the mean daily reservoir profile for each year, **Figure 3.17** breaks it down further by comparing each year by season to investigate the seasonality of ecologically important short term variability. **Figure 3.17** shows some variability between the years within each season, and in the annual profiles across the seasons. In relative terms, (i) **Winter** shows the highest amount of conformity in profile between the years, with the shallowest drawdown profiles, but set against a common daily and weekly profile. (ii) **Spring** in comparison has much larger drawdown extent for 2008-10, especially in 2008, but disparity between those years and 2011. Here, the 2011 average has all but lost the diurnal pattern associated with Cruachan reservoir handling, and displays shallow level fluctuations with weekly drawdown only reaching around 4m. (iii) **Summer** presents a contrasting profile whereby a diurnal and weekly profile exists for all years, but 2008 and 2009 display a shared pattern of long daily drawdown, then nightly reservoir recharge, whereas 2010 and 2011 have a much shallower profile, with low drawdown. As seen previously, 2010 fluctuates around a lower average reservoir level. Finally, (iv) **Autumn** displays an additional pattern of variability between the years, presenting a diurnal pattern for all years, moderate drawdown - being greater in 2008 and 2009, but a slightly 'blocky' appearance for some periods, potentially indicating common shorter term fluctuations.



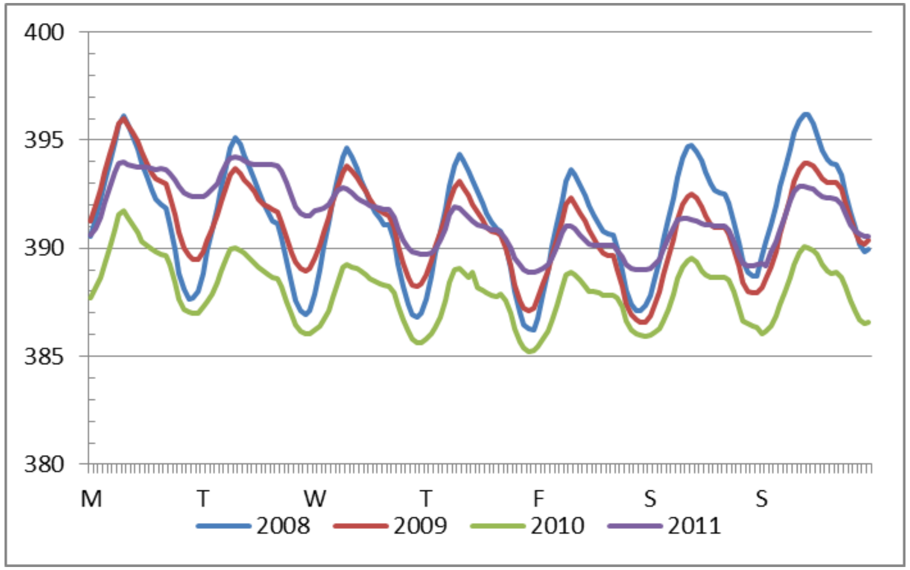
i) **WINTER**



iii) **SUMMER**



ii) **SPRING**

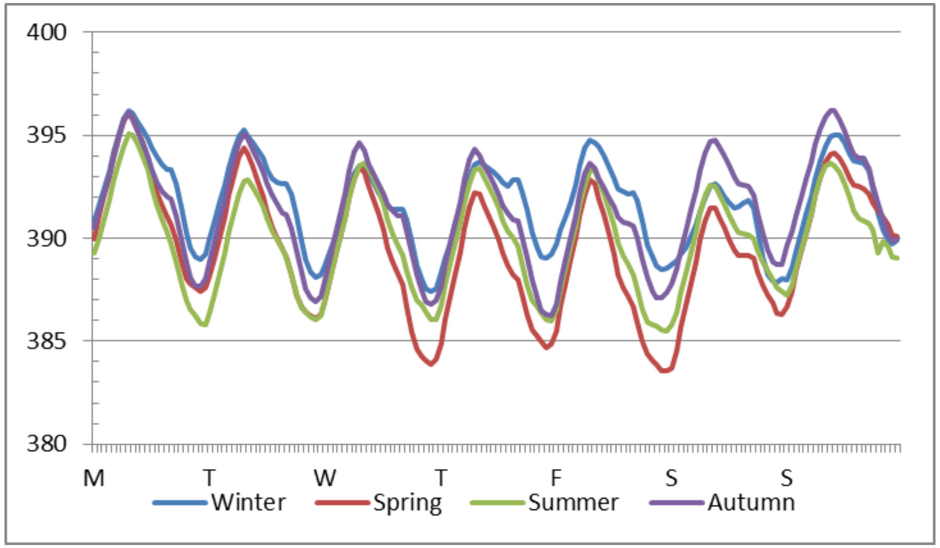


iv) **AUTUMN**

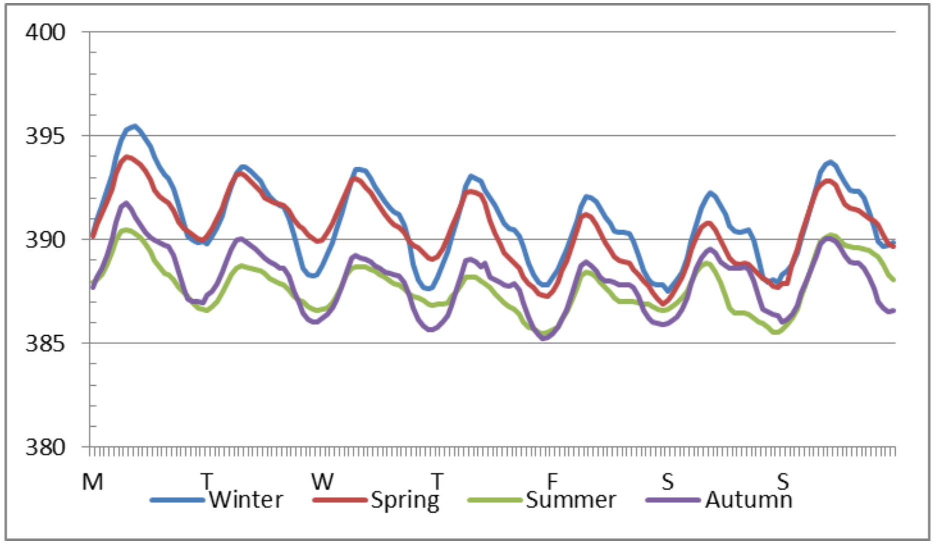
Figure 3.17: Mean weekly reservoir profile (m) by season (2008-2011)

3.7.3.1 Comparing seasonality within years

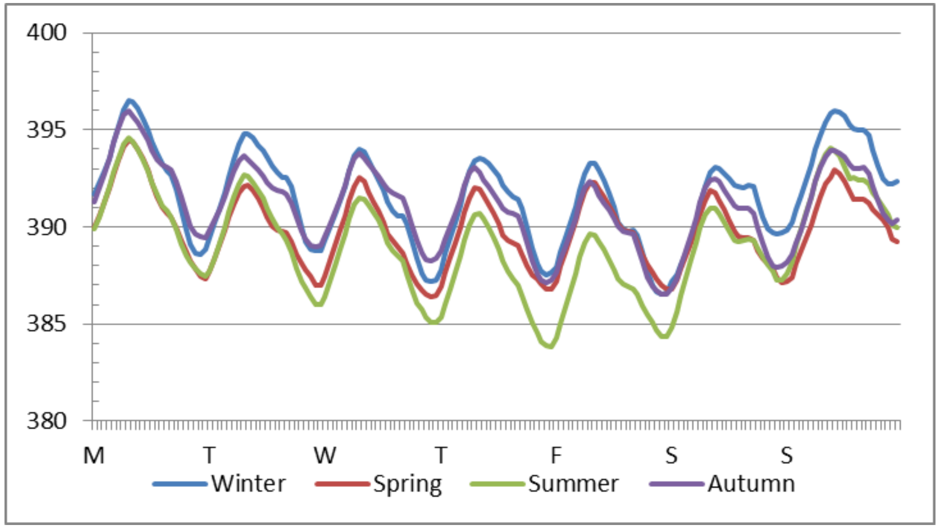
Having considered the average weekly profile for the whole of each year (**Figure 3.16**), in **Figure 3.18** we can also see the seasonal effect within each year. Other than in winter, (i) **2008** retains a profile for large diurnal drawdown across all seasons, with the spring profile presenting lower average reservoir level. (ii) **2009** again appears consistent between seasons, with some variability in the average reservoir level, where summer is lower than the other seasons towards Thursdays and Fridays, but the profile remains mostly the same. As we have seen, 2010 and 2011 begin to move away from the standardised diurnal and weekly patterns, towards more flexible, shallower drawdown - which is emphasised over the shorter, seasonal timeframes. Here, (iii) **2010** retains the classic, but shallow profile for winter and spring, but has a very shallow drawdown profile in summer and a 'flatter-topped' and blocky profile in autumn. (iv) **2011** also has significant variability by season, with winter displaying some features of a diurnal pattern, but mostly featuring very shallow drawdown and slight recharge at night. Again autumn, and to a lesser extent the other seasons, in 2011 are blocky and have flatter-topped daily peaks.



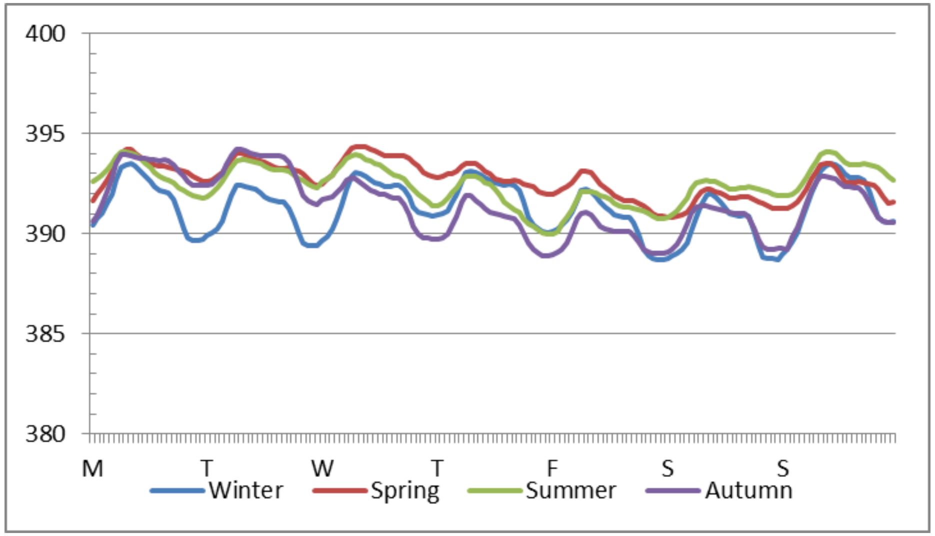
(i) 2008



(iii) 2010



(ii) 2009



(iv) 2011

Figure 3.18 Mean weekly reservoir profile (m) by year and season

3.7.4 Comparing raw data profiles

Due to the nature of obtaining longer term trends of short term variability, it is possible for smaller fluctuations to be averaged out and not represented. This may increasingly be the case given a potential tendency towards a more moderate yet dynamic operational approach, and its resulting reservoir profile.

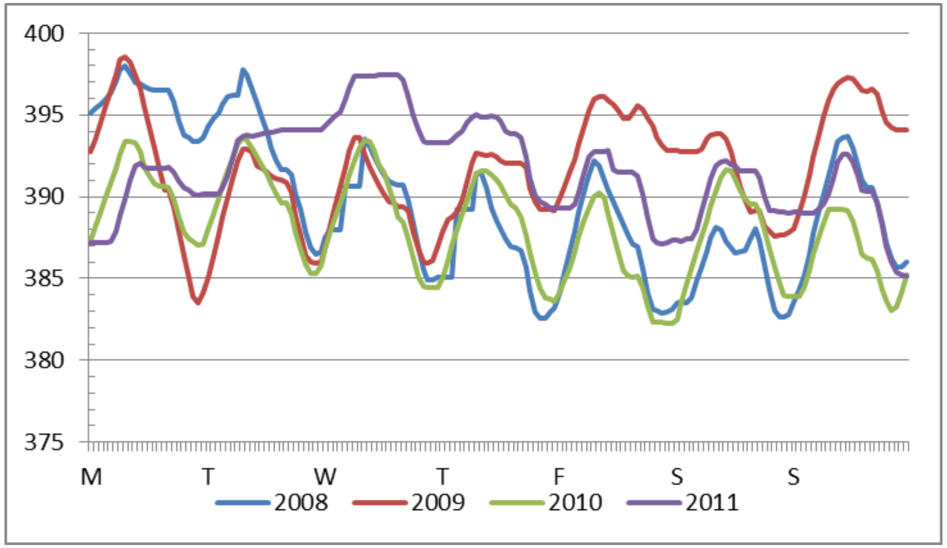
There is value then in comparing the 'actual' water level change profile at given strategic points through the year. **Figure 3.19** therefore presents the actual reservoir profile, comparing 2008-2011, for the first full week of four calendar months spread throughout the year. Here are four examples that provide further insight into the longer term trends and profiles, by presenting the snapshots of the underlying 'real-time' water level variability.

The first week of (i) **January** shows a fair degree of conformity in profile across the years, with 2008, 2010 and to a lesser degree 2009 displaying elements of the diurnal and weekly pattern. 2011 in contrast is much more erratic on a daily basis, with reservoir level seemingly not fluctuating on the Tuesday, then more of a blocky, moderate drawdown over the next few days.

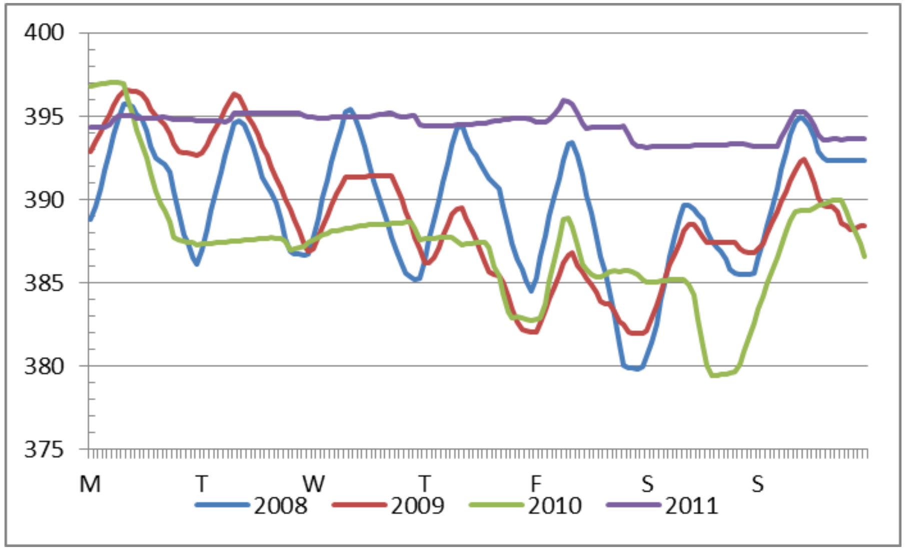
(ii) **April** shows 2008 as having a classic profile with long periods of drawdown through the day then recharge at night and at the weekend. 2009 follows a similar pattern, but with a much more moderate drawdown extent. 2010 and 2011 are much more erratic in profile, with 2010 undergoing severe drawdown on the Wednesday not occurring on any other day, and 2011 which undergoes a gradual drop in water depth over a few days, without much diurnal profile at all.

(iii) **July** presents a fairly classic reservoir profile for 2008 with long daily drawdown and a weekly and diurnal profile, with 2009 also doing so to a lesser degree and with reduced nightly recharge. Again 2010 and 2011 are much more erratic in their profile, with the 2010 daily drawdown only occurring at the beginning and end of the week, and 2011 being very stable with drawdown only reaching approximately three metres for the week.

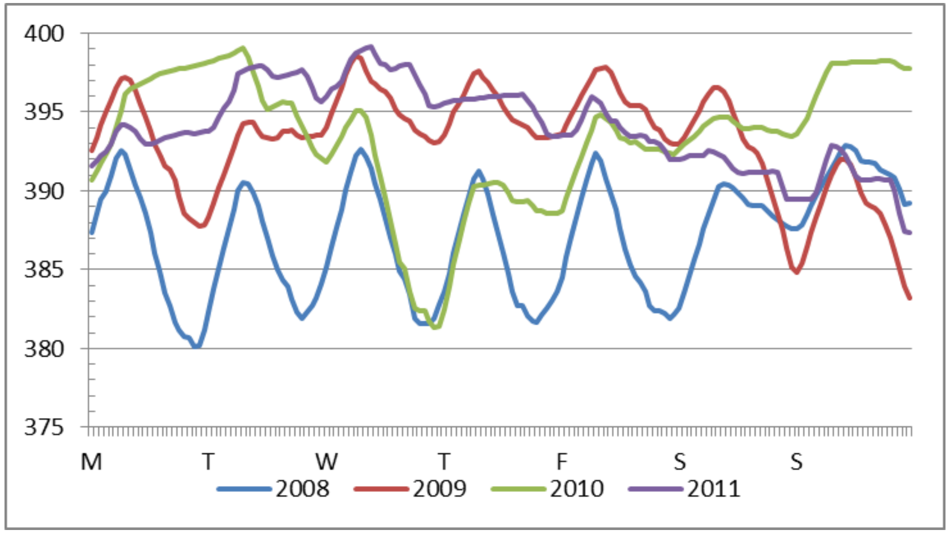
iv) Finally, **October** presents little conformity between years, or with the once standard Cruachan daily and weekly operational profile. Here, 2008 does exhibit a sense of diurnal operation, but with varying degree of daytime drawdown and nightly recharge. The same exists for 2009, and to a lesser extent 2010, but with increased 'idle' periods through the day where water level is flat-topped and shows no significant change. 2011 again is variable but not akin to a typical diurnal profile; rather it has moderate daily fluctuations differing by day throughout the week.



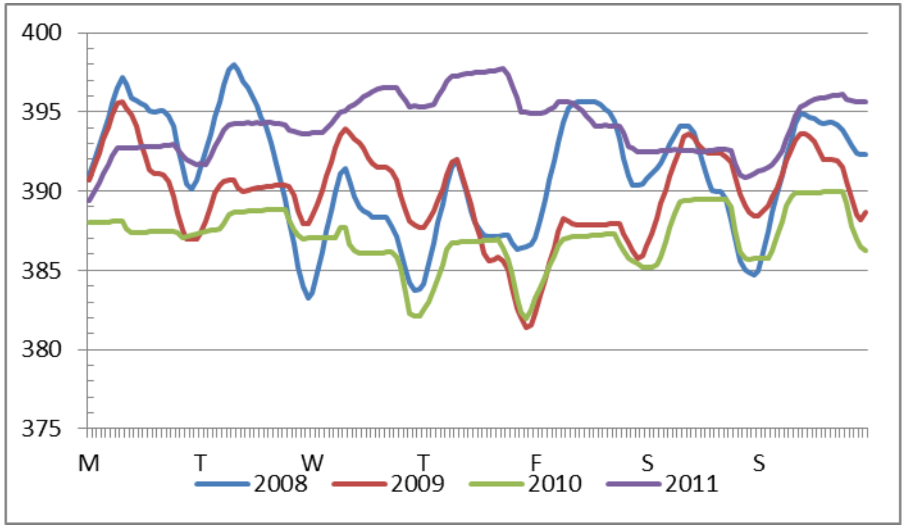
(i) January



(iii) July



(ii) April



(iv) October

Figure 3.19: Comparing actual reservoir profile (m) for the first full week of four calendar months, for 2008-2011

3.8 WATER LEVEL RESULTS SUMMARY

3.8.1 Drawdown parameters

The data showed no clear fluctuation in *annual* drawdown over the years considered, and subsequently no change in profile in relation to the Smith et al. (1987) annual benchmark, meaning the annual extent of water level remains the same. However over the shorter *weekly* and *daily* parameters, drawdown magnitude peaks in 2007 and 2008, and then subsequently falls over 2009-2011, down to 2001 levels. This less severe, reduced weekly drawdown from 2009 to 2011 brought conditions towards the Smith et al. (1987) weekly ecological benchmark. This reduction in *daily* drawdown from 2009 to 2011 is additionally shown to have a seasonal dimension, with the trend accentuated between the ecologically critical months of March to September. Variability magnitude (StDev) around the declining 2008-2011 daily drawdown average remains the same. In addition, 'aggregated' water level change (*total* fluctuations within a period) also decreased over this period.

3.8.2 Weekly water level profile

The historical weekly water level profile at Cruachan is confirmed to be characterised by long standardised daily drawdown, water level rise at night, and an incremental decrease in water level average throughout the week, before increased periods of reservoir recharge at the weekend. The years 2008 and 2009 were shown to have similar diurnal and weekly water level profile characteristics to the historical model for reservoir handling at Cruachan, with continuous uniform, long daily drawdown periods – leading to a more variable and quickly changing water level. By way of contrast, although on average exhibiting these basic characteristics in profile and timing, 2010 and to a greater extent 2011, are much more moderated and shallower in profile, exhibiting less flashy, slower fluctuations with reduced drawdown extent.

The trend over 2008-2011 for average weekly and diurnal water level profiles to shift away from the historical model does, however, show some underlying seasonal variation. Winter, for example, shows strong conformity across all years, and a more moderate profile against annual averages. In comparison, there is increased disparity in summer months with 2008 and 2009 retaining the classic weekly profile with large drawdown, but 2010 and 2011 displaying a much shallower, moderated profile. In comparison to 2008-9, when broken down by season 2010 and 2011 display average weekly reservoir profiles with much slower daytime drawdown resulting in flatter-topped and sometimes blocky curves.

These patterns and changes found in annual and seasonal reservoir weekly profiles are accentuated when considering weekly comparative snapshots of actual reservoir water level fluctuations. Here 2008 and 2009 tend towards long daily drawdown and fairly standardised weekly profiles, whereas 2010 and 2011 are much more erratic and display much shallower and slower drawdown periods, sometimes with little daily water level variability at all. There are some differences in the average level of water between years, around which the variability profile occurs, namely that 2010 appears to operate at a lower level.

3.8.3 Key messages

Whereas the years 2008 and 2009 retain the original operating profile of long, consistent diurnal fluctuations, daily and weekly drawdown is much lower in 2010 and 2011, especially in summer months, becoming more congruent with ecological benchmarks.

A recent transition exists for a shift away from the historical weekly water level profile of standardised long diurnal drawdown with incremental decreases over the week and recharge at the weekend, towards a much more erratic profile, with shallower and moderated drawdown with sometimes flatter-topped curves and idle periods.

3.8.4 A pattern of shifting reservoir profile characteristics

Although there is some uncertainty in the data, which will be addressed in the discussion, it shows an explicit transition from the water level profile seen in the historical approach, reflected also in 2008 and 2009, to the water level characteristics of 2010 and 2011. This shift in water level variability is summarised in **Figure 3.20**, where the profile has transitioned from long, standardised diurnal fluctuations, towards one which still retains the basic diurnal timings, but has a more moderated but erratic profile, with reduced drawdown speed and extent.

3.8.5 Attributing reservoir outcomes to generation approach

This investigation is based on the premise that for pumped storage schemes, reservoir variability and ecological outcomes are determined by the generation load profile. Given this transition in reservoir variability, we must consider what the associated generation approach at Cruachan now is, and how the wider changing electricity generation context has shaped this.

3.8.5.1 Shifting generation profiles at Cruachan

It is clear from the written literature (e.g. Sidebotham and Kennedy, 1990), and also from the recent 2008 and 2009 reservoir profiles, that the more 'historical' approach to generation consisted of a very standardised profile to meet the daily demand needs of the grid, delivering a pre-determined load using overnight base-load excess.

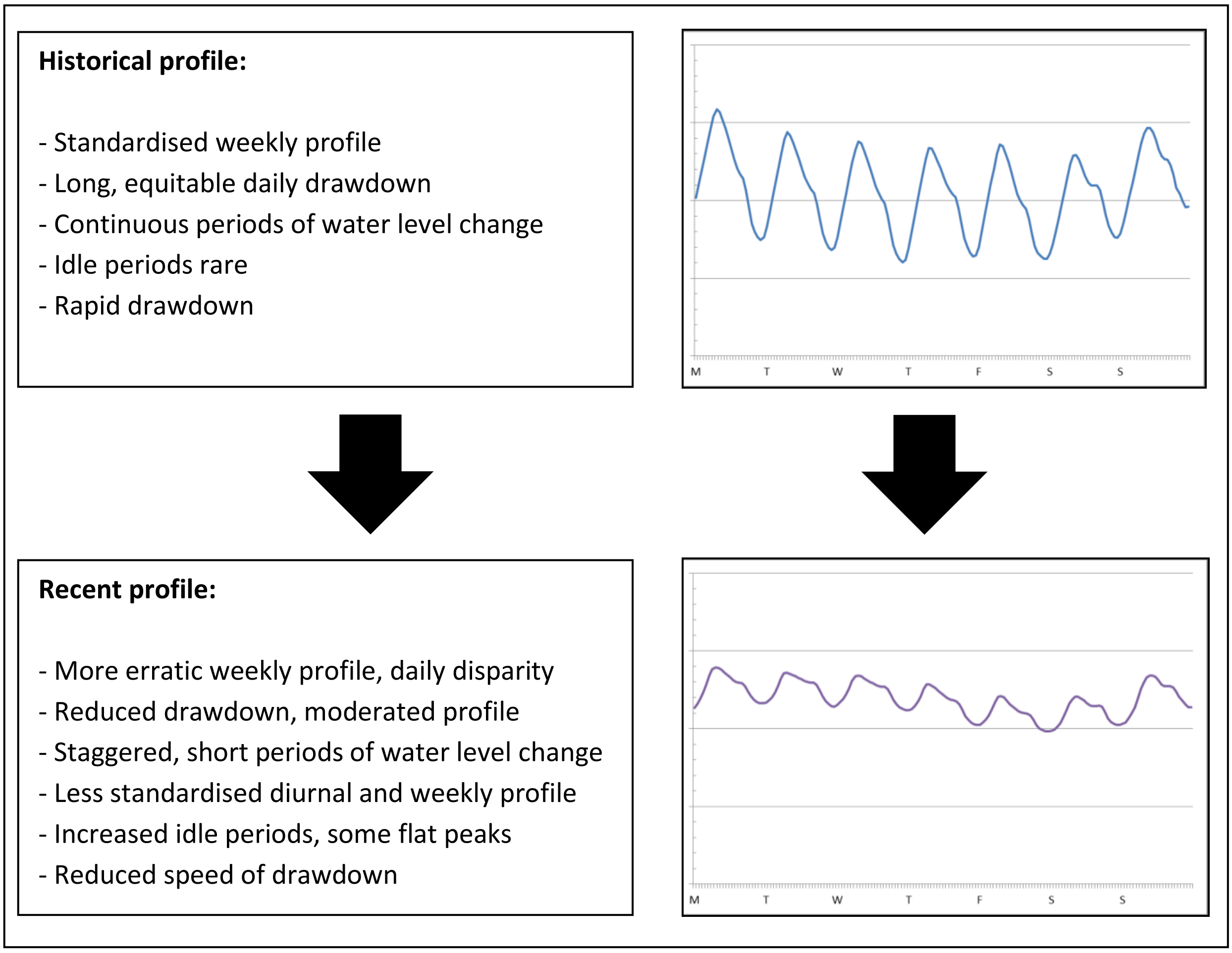


Figure 3.20: Characteristics of the historical and current water level profile

We know, however, that in the last few years, Cruachan has had two of its four units directly contracted to the National Grid to come quickly on line from spinning to meet short-term grid needs (B Wales 2012, pers. comm 22 November). This increased focus towards providing flexible and responsive, shorter-term loads is very much reflected in the recent reservoir profile, showing that generation is not targeted as much at consistent, predetermined periods, and does not occur in the magnitude seen previously. This means Cruachan generation has shifted from a focus on standardised demand periods, towards now being more orientated towards generation deficits, which are more changeable and intermittent. We can also see that unlike previously, nightly pumping does not occur as standard, but only when forced by low dam level, or when market conditions allow.

The seasonality of generation is also conveyed through the 2009-2011 reservoir variability data. Over the period winter generation remains consistent in timing profile, but compared to annual averages, 2008-9 has reduced generation (drawdown) magnitudes and 2010-11 has raised magnitudes. In comparison, summer months have raised generation magnitudes in 2008-9, and reduced, less continuous generation in 2010-11. It is felt that over this period, the seasonality to these generation profiles is shaped by the interplay between wider generation and demand forces, which will now be considered.

3.8.5.2 The role of the changing wider electricity generation context

The historical operational profile and, albeit to a lesser extent, that of 2008-9, were very much shaped by consumer *demand* needs. This position meant that there were long continuous periods of generation in the day, and pumping to recharge reservoirs during the night. We have seen from the reservoir profiles that 2010-11 is quite divergent from this - in line with the changing management approach to respond to short-term, un-scheduled grid needs that are determined by *generation* shortfalls.

The examination of wind power output trends showed that although wind power output in the UK generally matches up with demand needs, the short-term volatility of output remains as a factor for grid efficiency. Accordingly, as wind power becomes an increasing proportion of the mix, grid balancing must become increasingly flexible and responsive. However, although the penetration and increasing proportion of wind in the mix, and any associated response from balancing elements, is incremental, the decision taken by Cruachan and the National Grid, seemingly at the start of 2010, to be much more responsive and flexible, has caused a step-change in generation approach at the scheme. This new 2010-11 philosophy to Cruachan operation in general is shaped to a greater degree by short-term generation deficits, which require flexible and responsive generation loads.

In addition to this interplay of demand and generation as wider contextual forces shaping the operational characteristics at Cruachan on an annual scale, their relative influence is also seen over a seasonal scale. **Figure 3.21** seeks to take the findings from the seasonal variability in water level (see **Figure 3.12)** and thus generation profile and attribute them to the changing influence of generation and demand for the three different operational periods. Although creating a somewhat artificial distinction between the periods, and assuming the original historical profile is consistent all year round, this approach helps us to identify and unpick the changing wider influences, whilst also keeping in mind the step-change operational approach taken from 2010 (conveyed by the double lines).

Season		Original	2008-9	2010-11
	Summer	- Lower demand - **High** Drawdown	- Lower demand - Lower wind - **High** drawdown	- Lower demand - Lower wind - **Low** drawdown
	Winter	- High demand - **High** drawdown	- High demand - High wind - **Moderated** drawdown	- High demand - High wind - **Moderate to low** drawdown
		Operational period		

Figure 3.21: The changing relative influence of wind (generation) and grid demand over operational periods, and seasons

In **Figure 3.21**, and as discussed previously, the 'original' operational profile was driven by a need to meet demand peak. The result was high drawdown, and long continuous generation during the day for both summer and winter (as per **Figure 3.15**). In the '2008-9' period, however, wider grid generation and the output of technologies such as wind have begun to exert an influence on the operational profile. In winter, when there is additional output from wind generation (**Figure 3.5**), but also when demand peaks are greater (**Figure 3.6**) the outcome is that generation and drawdown becomes slightly moderated. Seemingly this is due to both forces (generation and demand) now influencing and shaping generation, resulting in a transition towards the moderated profile outlined in **Figure 3.20**. For 2008-9, this dynamic is less acute in summer, so operational characteristics revert to high drawdown as in the original phase.

Finally, in the '2010-11' phase of **Figure 3.21**, whereas the summer conditions are the same as in 2008-9, or albeit with increased wind penetration, the Cruachan operational approach has been altered so as to focus on generation shortfalls. Similarly, in winter with high demand peaks, and a general raised seasonal output from wind power, due to the operational intervention we see much more of a transition to lower magnitudes and shorter-term generation, despite conditions being similar to that of 2008-9.

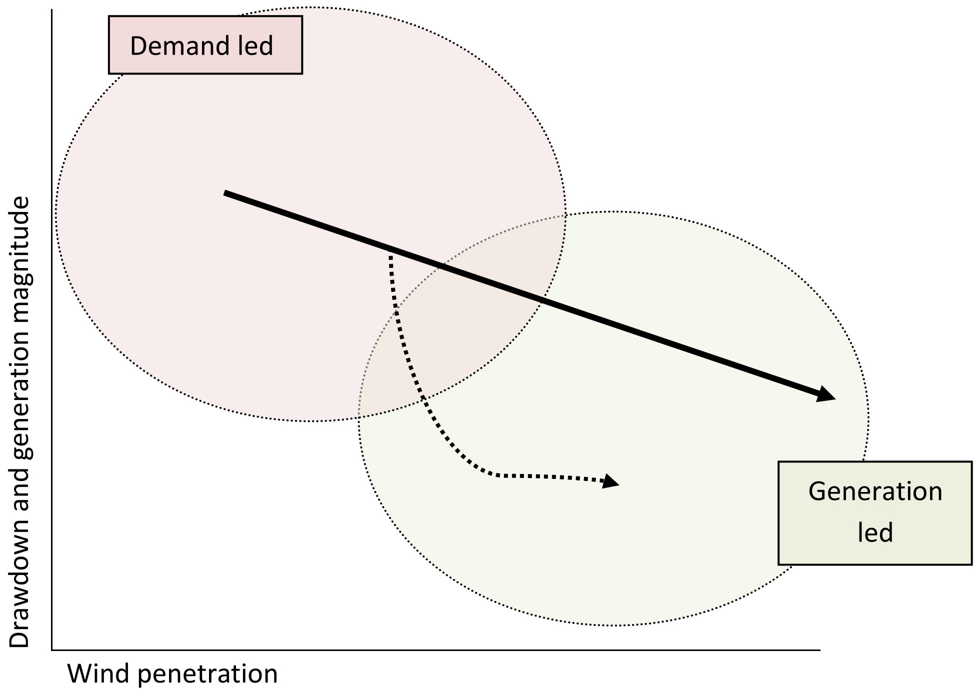


Figure 3.22: General relationship between wind penetration and Cruachan generation magnitude, including divergent outcome from operational intervention (dotted line).

The generation magnitude outcome from being orientated towards demand peaks, or generation shortfalls is represented pictorially in **Figure 3.22**. This transition between the two influences is overlaid on the negative correlation between wind penetration and Cruachan generation magnitude that we have found here – namely that as there is further wind penetration into the UK mix, the operational intensity and use of continuous drawdown periods declines. As discussed and highlighted in **Figure 3.21** however, the incremental transition between being *demand* led, with long drawdown and larger magnitudes of generation, and *generation* led, with more short-term, responsive and flexible operation, is to a degree decoupled by the management change at Cruachan to have two units on standby specifically for short term needs, as depicted by the dotted line.

In summary, as wind power and other intermittent renewable generation become a greater proportion of the national generation mix, the operational focus of Cruachan has transitioned from being demand led, resulting in long, standardised generation periods, to being generation (deficit) led, with a much more flexible and short-term generation profile. This research is concerned with exploring the linkages and fostering communication between energy and water disciplines, and communicating the ecological significance of changing water level profiles, but in a format that can aid decision making. Given the trends outlined here, it is important to relate these back to ecological and regulatory challenges, for Cruachan and elsewhere.

3.8.6 Linking reservoir outcomes to ecological challenges

The methodology utilised for this study seeks to identify ecological outcomes from the changing generation and water level profile at Cruachan. The starting point for this has been the identification and justification of ecologically significant indicies for water level change (Bragg et al, 2003), which were applied against quasi-benchmarks (Smith et al., 1987) and seasonal ecological sensitivities (Sniffer, 2006). The result is the identification of a categorical response (King et al., 2003) that works to overcome uncertainties regarding specific localised thresholds, and ascertain if the changing water level profile is becoming convergent or divergent with conditions likely to support the integrity of ecological elements.

This study has identified a transition in the generation approach at Cruachan, which is being driven by the growing challenge of integrating an increasing proportion of renewables on the grid. The water level characteristics of the historical 'old' approach that is also to a degree reflected in 2008-9, and also the 'new' approach of 2010-11, are summarised in **Figure 3.23** in a format that relates them back to the elements of the ecological indicies, hydrological factors and seasonality. From this comparison we can identify the ecological implications of the transition in water level variability at Cruachan from the changing generation approach, by identifying a categorical outcome for each element of water variability.

Figure 3.23 conveys that for the key elements of water level variability (Sniffer, 2006) , three (duration, magnitude and timing) exhibit a distinct convergence with benchmarks, so offer improved conditions, and one (frequency) shows no large gain or loss. On this basis, the transition shows that overall conditions are becoming much more moderate and less extreme, and consequently offer increased potential to support a higher degree of ecological integrity and functioning. For example as outlined, macrophytes are sensitive to altered water levels, where distortions to the character and rate of change can affect littoral populations and succession in marginal plant areas. In addition, the period February to September presents heightened habitat sensitivity as they undergo flowering and seed dispersal, supporting longer term ecological integrity.

Ecological elements	Seasonality **	Nature of deviation from reference conditions *	Hydrological factors	Hydrological parameters	Key elements of water level variability *	Hydrological indicies		Key profile characteristics comparison	Categorical outcome
Macrophytes	Growth, flower and seed dispersal in March-Sept	Succession in marginal plant communities	Altered water level, max and min depths	Rate of change	**Duration**	Flow duration curve	Old	Steeper FDC, indicating a more variable and changing water level profile	Less rapid change supporting greater littoral integrity
		Reduced growth of submerged macrophytes	High water level				New	Flatter FDC, indicating slower and more moderate water level change	
		Deviations in litoral macrophyte populations	Distortions to character and rate of water level fluctuations	Extent of change	**Magnitude**	Drawdown	Old	Large continuous, rapid and standardised daily and weekly drawdown	Lower magnitude of change supporting greater littoral integrity
							New	Reduced daily and weekly drawdown, towards benchmarks. Slower water level change	
Invertebrate fauna	Nymphs in shallow water Feb-Nov	Deviations in benthic invertebrate communities	Distortions to character and rate of water level fluctuations	Water level profile	**Timing**	Seasonality	Old	Historically constant profile all year round, with slight moderation in winter 08/09	Seasonality accentuates the positive ecological outcomes
							New	Decline in mean daily and weekly drawdown accentuated from Mar-Sept, towards ecological benchmark	
Fish fauna	Mostly spawning / nesting March - Aug. Except winter Charr	Distortions to spawning success	Distortions to character and rate of water level fluctuations	Water level fluctuations	**Frequency**	Aggregated change and StDev	Old	St Dev ≈ 33% of daily drawdown mean. Aggregated daily water level change propotional with DD	Frequency of fluctuations not overly affected, moderate outcomes
							New	St Dev ≈ 60% of lower daily drawdown mean. Agg daily water level change propotional with DD	

Figure 3.23: Assigning categorical ecological outcomes to the changing reservoir profile (*Sniffer, 2006; ** Bragg et al., 2003)

The study shows that the newer generation approach at Cruachan results in water level variability that has a slower, less flashy rate of change, and has reduced short-term drawdown magnitudes, a trend which is accentuated between March and September. Invertebrates displaying similar water level sensitivities with additional seasonal characteristics due to nymphs in shallow water from February to November, and summer reservoir spawning fish fauna, would also appear to benefit from these altered characteristics in operational profile.

3.8.7 Regulatory and policy implications

Scotland holds more than 90% of the volume and 70% of the total surface area of the UK freshwater resource, spread over 30,000 water bodies. The interplay of climate, altitude, geology, soil type, landform and land use has resulted in an internationally significant diversity of fresh waters and associated habitats and species (Mackey and Mudge, 2010). Planning consent for new hydropower proposals is informed at a strategic level by sensitivity mapping, highlighting spatial elements such 'Natura sites', reflecting internationally important natural heritage habitat and species (SNH, 2011). Although protection of priority habitats and species in this way is critical to deliver sustainable renewable energy, this research is orientated towards existing peaking hydropower schemes, that may be located on engineered and 'heavily modified' water bodies.

The emergence of thinking around ecosystem services (Maltby et al., 2011), and the transition towards integrated, catchment level water resource decision making (Holmes et al, 2005) has demonstrated the need to go further than perhaps single issue, priority habitats, to increase rather the general level of biodiversity to support well-functioning ecosystems and to maximise the benefits and contribution to sustainable economic growth (Scottish Government, 2012).

As is the case with hydropower, many highly managed ecosystems provide important ecosystem services (Maltby et al., 2012), but increased biodiversity can reduce pressure on ecosystems, habitats and species, making ‘space’ for often fundamental natural processes (Scottish Government, 2012). The EU Biodiversity Strategy (European Commission, 2012) highlights that by working innovatively with nature we can create opportunities to reduce costs and secure multiple benefits for society. This research informs our understanding of our relationship with natural resources and offers applications for the interaction of policy areas at a scheme level directly at Cruachan, but also elsewhere and at a more strategic level.

Due to the original magnitude and frequency of water level change at Cruachan there were severely impoverished littoral communities of macrophyes and zoobenthos (Smith et al., 1987; Smith, 1980). This study has shown that the changing operational profile has led to a more moderated regime, with slower rates of change and reduced drawdown magnitude. Although the Smith et al. (1987) benchmarks are not achieved, which would indicate fully viable conditions, there has been an improvement in the ability of the water level regime to support increased ecological functioning and biodiversity. Mean weekly draw down for example has changed from 15m in 2008 to 8.5m in 2011, presenting progress of 45% towards the Smith et al. (1987) benchmark of 0.5m.

Climate change presents conditions of change and uncertainty, both in terms of impacts and mitigation efforts, meaning there is a need to identify and highlight value in the water environment to maintain essential services (Maltby et al, 2011). Being able to identify and deliver on aligned goals, across a number of agendas such as supporting biodiversity and service delivery helps to secure natural resource integrity as we transition to a healthy low carbon economy.

It has long been appreciated that local hydrological conditions (Gilvear et al., 2001; Marsh and Anderson, 2001) and scheme operation and characteristics (Petts, 1984) combine to shape the implications from hydropower. This is especially true of peaking and pumped storage schemes where water level change is inextricably tied to generation.

Given the wider grid transition towards a greater proportion of renewable generation, it is suggested here that other peaking and pumped storage schemes in Scotland and the UK will undergo a similar shift in their generation and reservoir management approach. Installations such as the 100MW Glendoe conventional scheme and the recently proposed Coire Glas (600MW) pumped storage scheme are both flexible generators where we could see similar moderate, but flexible short-term generation and resulting reservoir profiles.

3.8.8 Data limitations

It is unfortunate the daily resolution data from 2001-2007 was patchy, so some years (2002, 2003, 2005, 2006) were insufficiently robust to use in this study. This incomplete data means the pattern of drawdown from 2001 to 2011 is unclear and somewhat mixed, as it peaks in 2007-8 then falls in 2010-11 back down to a 2001 level, which cannot be explained fully here.

The higher resolution data from 2008-2011 however enables a more robust examination of changes in reservoir variability. It displays that over this period, coinciding with reported change in balancing orientation, that there has been a transition to the more moderated recent profile. In addition, when comparing this recent moderated profile to the historical approach outlined in the literature (e.g. Sidebotham and Kennedy, 1990) this trend is also shown.

This chapter has considered the influence of a changing wider energy mix on the generational profile at Cruachan. It has acknowledged in that consideration that rather than this occurring gradually, against these wider trends, specific management and operational decisions will in fact be made at Cruachan and nationally, that result in step changes to this transition. On that basis, it is suggested here that whilst there is unfortunately some noise, or distortion in the trends conveyed here, ultimately it is clear that there has been a transition in scheme operation that is down to the differing grid needs under a renewables agenda.

3.9 FUTURE COMPOSITION OF GENERATION IN THE UK AND SCOTLAND

The above examination of historical electricity generation composition in the UK and Scotland highlighted the increasing penetration of renewable technologies such as onshore wind. The EU's Renewable Energy Directive (2009/28/EC) is one of a number of high level policies that drive this transition to a low-carbon society, committing the UK to supplying 15% of its energy consumption from renewable sources by 2020, equating to about 30% of electricity generation. It is projected that the UK will be able to meet this obligation under a 'medium' renewable uptake scenario (AEA, 2010). However a key issue for this present research is to identify the technological composition of these potential future generation scenarios, and examine how they will shape the future operational and water management profile of grid elements such as Cruachan.

Previously, under the Non-Fossil Fuels Obligation (NFFO) and early iterations of the Renewables Obligation (RO), less-mature technologies such as off-shore wind lacked competitiveness as there was no technological 'banding', stifling innovation and uptake compared with established technologies such as hydropower and onshore wind (Foxon et al., 2005). Subsequently, with banding and favourable incentive weighting, delivering on the substantial off-shore wind resource base is central to future renewable generation scenarios. Although driven by stringent climate change targets, future increased renewable penetration, specifically the significant contribution of wind power, will exist alongside a wider electricity mix with a differing composition of conventional technologies from today, as around a fifth of generation capacity available in 2011 will close by the end of the decade (DECC, 2012c).

3.9.1 UK generation – Gone green scenario

The UK National Grid's (2011) *Future Energy Scenarios* document conveys scenarios for the potential future energy composition of the UK, broken down into generation fuels for electricity, heat and transport up to 2030. Their 'Gone Green' scenario represents a balanced approach to meeting renewable energy and CO_2 emission targets in 2020 and 2030, in which the necessary contribution is made from the energy sectors. This scenario is compatible with the DECC Renewables Roadmap (National Grid, 2011b).

TWh	2010	2015	2020	2030
Nuclear	66	53	69	121
Oil	0.4	0	0	0
Tidal	0	0	3	14
Hydro	5	6	6	6
Gas	144	147	133	50
Coal	104	91	32	25
Biomass	11	18	24	29
Wind onshore	9	20	30	34
Wind offshore	2	13	50	112

%	2010	2015	2020	2030
Nuclear	19	15	20	31
Oil	0.1	0	0	0
Tidal	0	0	1	4
Hydro	2	2	2	2
Gas	42	42	38	13
Coal	31	26	9	6
Biomass	3	5	7	7
Wind onshore	3	6	9	9
Wind offshore	1	4	14	29

Table 3.6: UK Electricity Generated by technology - Gone Green Scenario (TWh and percentage) (National Grid, 2011)

The electricity generation contribution (TWh) and mix proportion (%) by technology under the UK's Gone Green scenario for the years 2015, 2020 and 2030 is set out in **Table 3.6** and presented visually in **Figure 3.24**. Providing insight into an achievable future generation scenario, it outlines the diminishing contribution of coal, and to a large extent gas, being replaced by more nuclear and offshore wind. On this national scale, the significant future role of offshore wind generation is immediately apparent, accounting for 4% in 2015, 14% in 2020 and 29% in 2030, just behind the contribution of nuclear at 31%.

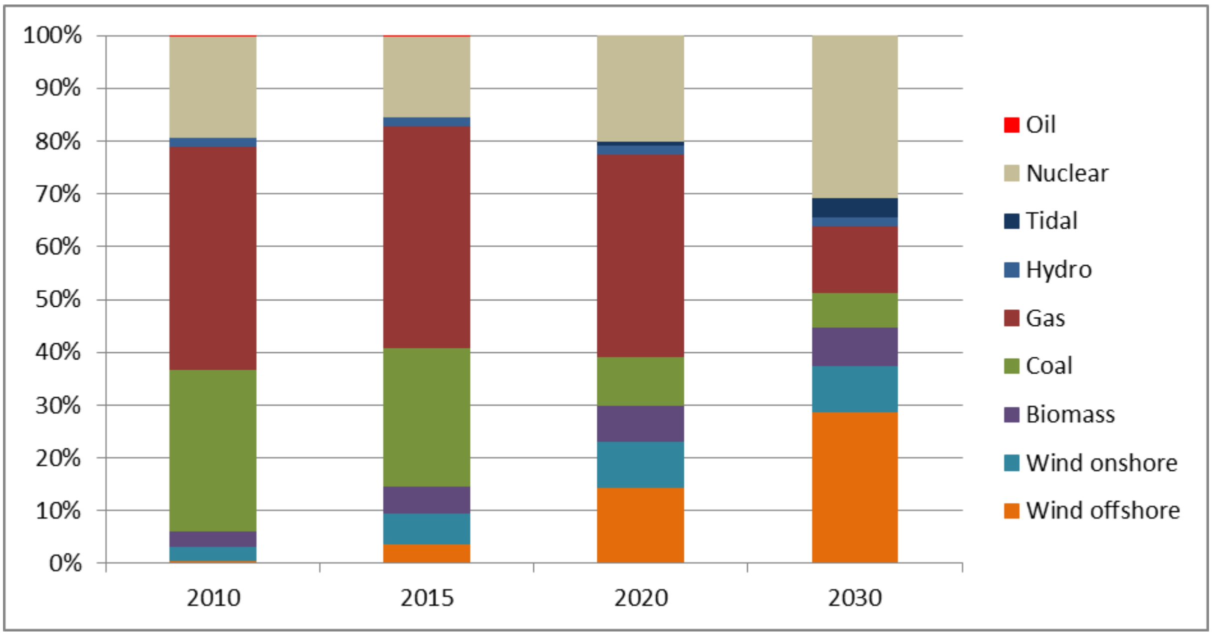


Figure 3.24: UK Electricity generation by technology – 'Gone green scenario' (% of mix) (National Grid, 2011)

3.9.2 Scottish generation – Moderate scenario

Although part of the UK, equivalent scenarios exist for Scotland, (Scottish Government, 2010b), as part of number of documents including the 2020 Renewables Routemap (Scottish Government, 2011). **Table 3.7** and **Figure 3.25** presents data from 'Scenario one' which is a moderate view of how renewable energy could grow in Scotland to meet the current 2020 targets. This view is based on the utilisation of established potential, a growth trajectory that is not overly ambitious and the realisation of development opportunities currently underway (i.e. marine energy).

In this 'routemap' again we see the emerging dominance of wind power, but interestingly the emphasis is on onshore generation, but with offshore also playing a role. In this scenario, total wind generation accounts for 34% in 2015, 43% in 2020 and 61% in 2030. Due to a differing political landscape, whereas coal and gas continue to fall as in the wider UK projections, the future generation mix in Scotland does not include nuclear. This difference leaves a greater reliance on renewables, albeit with increased diversity with technologies such as wave and biomass and CHP making a smaller contribution.

TWh	2008	2015	2020	2030
Nuclear	14	9	8	0
Tidal	0	0	1	1
Hydro	3	3	3	3
Gas	7	8	7	3
Coal	15	6	5	3
Biomass	1	1	2	4
Wind onshore	5	13	17	20
Wind offshore	0	2	5	11
CHP	2	2	3	4
Other	1	0	0	0
Wave	0	0	1	1

(%)	2008	2015	2020	2030
Nuclear	30	19	15	0
Tidal	0	0	1	2
Hydropower	6	6	6	6
Gas	14	19	13	6
Coal	31	14	10	6
Biomass	2	2	4	7
Wind onshore	11	30	33	40
Wind offshore	0	4	10	21
CHP	4	4	6	8
Other	1	1	1	1
Wave	0	0	1	3

Table 3.7: Scottish Electricity generated by technology - Scenario one (TWh and percentage) (Scottish Government, 2010b)

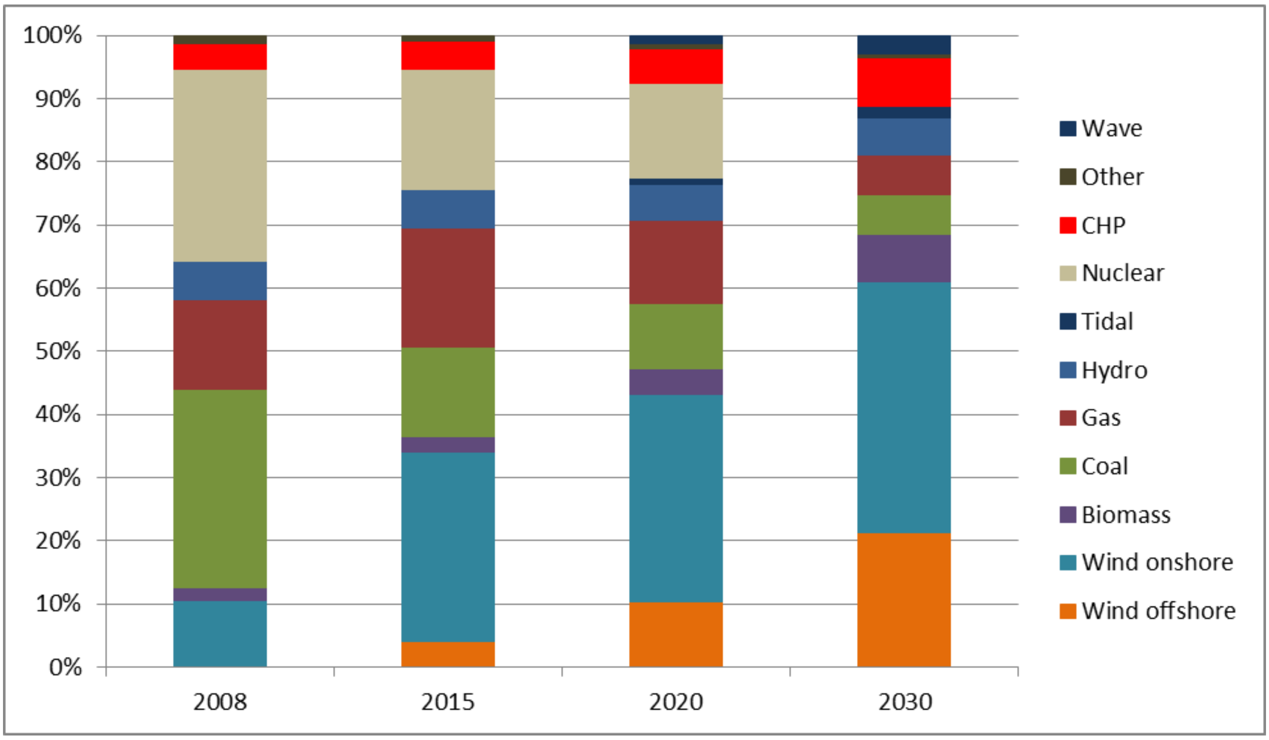


Figure 3.25: Scottish Electricity generation by technology – Scenario One (% of mix) (Scottish Government, 2010b)

The scenarios presented here offer a moderate, obtainable and balanced approach to a generation mix that will obtain the medium term 2020 obligations, integrating renewables but also allowing for the reality of continued fossil fuel use. Through these scenarios, it is possible to examine the ways in which the operational and reservoir management of Cruachan could be shaped by this changing wider generation context in the future.

3.9.3 The influence of a future generation mix on Cruachan

As inherent technological diversity supports grid efficiency (IEA, 2005), the increasing dominance of wind generation, the output profile of which being especially limited by environmental conditions (Albadi and El-Saadany, 2010), leads to an increasing pressure on reserve elements of the network such as Cruachan (Ilex, 2002; Mott Macdonald, 2003).

3.9.3.1 Changing generation system capacity factor

A capacity factor (cf) of a power plant is an expression of the amount of electricity produced over a period, as a percentage of its theoretical maximum in line with its installed capacity. A lower capacity factor for an individual scheme is indicative of either a load following orientation, one that has undergone outages or maintenance over a period, or crucially for this study, one whose output profile is more variable, perhaps through environmental conditions. The variability in capacity factor between technologies provides insight into their relative output profile, and perhaps instability or variability in supply. With renewables dominating a future technological composition of the grid, it is valuable to consider the changing average or 'system' capacity factor for the grid as a whole, allowing insight into the projected generational stability and output profile of the network, thus enabling the identification of trends and context that shape the operational characteristics of Cruachan.

Taking the generation composition under the above moderate scenarios for the UK (National Grid, 2011) and Scotland (Scottish Government, 2010b) and proportionately applying the associated capacity factor by technology highlighted previously (**Table 3.3**) (DECC, 2012), including current figures for tidal (MCT, 2012) and wave (Pelamis Technology, 2012), **Figure 3.26** presents the resulting projected system wide capacity factors up till 2030.

The clear trend presented is that the projected changing generation composition results in a reduction in the system capacity factor at a UK and a Scottish scale. Under the UK 'Gone Green' scenario the system wide capacity factor drops from 54% in 2010 to 46% in 2030, whereas under the Scottish equivalent ('Scenario One') there is a more acute decrease from 48% to 35%.

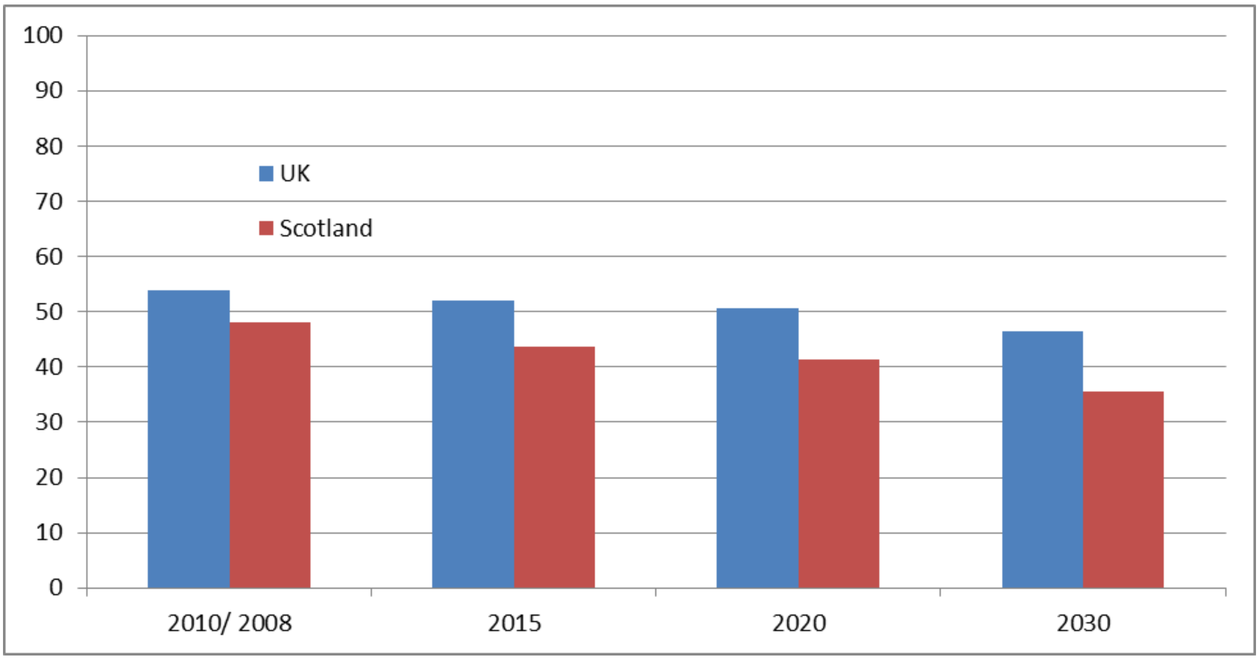


Figure 3.26: Generation grid system capacity factor (%) for Scotland and the UK, under corresponding moderate renewables uptake scenarios up till 2030

This reduction is explained by the changing generation composition and relative technological contribution across the scenario periods, towards increased wind led renewable penetration. On the UK scale scenario, the large contribution by gas (cf of 62%) and coal (cf of 42%) is being mostly displaced by renewable technologies with a much lower capacity factor, namely offshore (cf of 28.2%) and onshore (cf of 26.2%) wind. A similar pattern exists in Scotland, but without nuclear (cf of 60.1%) to buffer the overall figure as it is phased out by 2030, in addition to a greater emphasis being placed on *on*shore wind technology, which has a lower capacity factor than *off*shore wind.

Whilst we are projecting some 20 years into the future and there may be developments in technologies and their efficiency, it is felt the capacity factor of these technologies will not change proportionally enough to distort this analysis.

This scoping analysis is conducted using generation proportions and percentages to examine the changing grid composition. It should be noted however, that in real numbers demand and especially peak demand will increase up to 2030, putting additional pressure on the balancing and integration elements of the grid (DECC, 2012c).

3.9.3.2 Cruachan under future renewable scenarios

Although sometimes attributable to individual technologies that are load following (peaking) or suffering outages and maintenance, it is clear that the key driver here in the reduction of the *system* capacity factor is the transition to wind dominated grid composition – which is more sensitive to environmental conditions. The consequence from this trend is that the overall generation output of the grid is less stable and consistent, with increased variability and intermittency. One key implication of this likely situation is that as capacity factor drops in this way, and there being less inherent diversity in the grid, there is a greater need for 'active' balancing measures, integrating the output profile of renewables with demand characteristics.

The increased penetration of renewables is often described as requiring efficient integration into the wider demand profiles of the grid (IEA, 2005). Awareness of this requirement has led to renewed interest in existing pumped storage schemes and their future operational profile (Deane et al., 2010). This position is demonstrated well here by the trend for a lowering of the generation system capacity factor under a future renewable transition for the UK and Scotland. Crucially therefore, whereas the historical generation profile of Cruachan was orientated towards *demand* needs

(Sidebotham and Kennedy, 1990), and as previously demonstrated in this study the transition to increased renewables has led to a greater emphasis on the *generation* profile of the wider grid, this examination of the implications of the future scenarios highlights that the wider generational context will increasingly shape the operational demands at Cruachan. Therefore, to accommodate these future scenarios, the generation and reservoir management of Cruachan would need to become even more flexible and less standardised, with shorter term water level change, with slower drawdown that is less extreme in extent. Interestingly, although the generation grid is UK wide, the Scottish scenario presents a slightly lower capacity factor than the UK, suggesting that this transition and challenge for Scotland, being close in proximity to Cruachan, is even more acute.

3.9.4 Water resource management in a changing world

The context and pressures on water resources are very much shaped by external socio-economic forces and policy sectors such as energy (Volkery et al., 2011). This case study has sought to engage with this dynamic, but crucially examine the potential for change, as Scotland and the UK transitions to a renewables dominated, low-carbon society. For sustainable renewable energy, the role of governance is to reconcile the benefits of hydropower with the tensions and trade-offs for freshwater ecosystems (Reid et al., 2004). It is important therefore to understand the trajectory of the wider generation context to be able to identify and manage future fresh water resource pressures and challenges. The evidence presented here suggests that Cruachan, and arguably other peaking hydropower schemes, are increasingly going to have less standardised, slower and shorter term water level change, which is less extreme in extent over diurnal periods.

Climate change mitigation and adaptation provide distinct high-profile areas that shape policy direction and objectives, and also our relationship with natural renewable resources into the future. However, this research at Cruachan has demonstrated that there are complex, often unforeseen feedbacks relating to the pursuit of low carbon generation, which affects our patterns of use of hydrological resources. Efforts are underway to orientate Scotland as a ‘Hydro Nation’, to deliver on economic opportunities and good natural resource stewardship, in a changing and often stressed hydrological world (Scottish Government, 2012b). It outlines that leadership and a strategic vision are needed to identify and deliver on a low-carbon water industry for the next 10 to 20 years.

From the findings here, it is argued that this kind of strategic forward thinking sectoral modernisation must also engage with the interaction between policy areas, now and into the future. Such engagement will allow for greater policy integration and enable efficiency savings and ‘win-win’ opportunities to be identified. As a result, understanding the full value and water resource services can only be realised through understanding our current, but also future relationship with it.

CHAPTER 4: AN ASSESSMENT OF HOW RENEWABLE ENERGY INCENTIVES HAVE SHAPED THE SUSTAINABILITY OF HYDROPOWER IN SCOTLAND

4.1 INTRODUCTION

Following the emergence of hydropower in Scotland in the early 20th century, then the significant period of hydropower development in the 1950s and 60s under the North of Scotland Hydroelectricity Board (NoSHEB) (Payne, 1988), the last 25 years has seen further expansion under the climate and renewables agenda. This new expansion is supported by policy mechanisms that incentivise hydropower as a renewable source of clean electricity. Hydropower of all scales, however, is understood to alter a river's natural flow regime, affecting its downstream physical, chemical and biological characteristics (Petts, 1979). As a result, governance mechanisms must reconcile the benefits of hydropower with the tensions and trade-offs for freshwater and natural heritage integrity (Reid et al., 2004). Whilst looking to align Scotland at the forefront of renewable energy uptake in Europe, Scottish Ministers therefore advocate 'sustainable renewable energy', to minimise potential trade-offs and take a proportionate approach (Scottish Government, 2012), maintaining water ecosystem health and service value.

It is commonly understood that the implications from hydropower are shaped by local hydrological conditions (e.g. Gilvear et al., 2001; Marsh and Anderson, 2001), and scheme design and operational characteristics (Petts, 1984). However, despite the influential role of incentives, other than reviews of the mechanisms and policies themselves (e.g. Mitchell, 1995; Connor, 2003; Mitchell and Connor, 2004), research into their effectiveness at supporting hydropower (e.g. Harrison, 2005), and related regulatory reports (e.g. Ofgem, 2012), there has not been an examination of the way in which differing incentives help to shape the potential trade-offs and sustainability outcomes from hydropower at a scheme and a national level.

Given this interaction of energy and water policy at all scales (Volkery et al., 2011), an increased understanding of the way in which incentives frameworks shape any resulting pressures on freshwater ecosystems is of key relevance to sustainable water regulation and integrative decision making. With incentives remaining a key aspect of government renewable policy for a range of technologies (DECC, 2012a), this research will also inform debate surrounding the shape and application of these frameworks now and into the future.

This research therefore provides an evaluation of the emergence and development of incentive mechanisms for their role in shaping the sustainability characteristics of hydropower at a scheme and national level. It will examine the aims, structure and delivery of these mechanisms for their influence on scheme characteristics, as well as operational and river management challenges for hydropower in Scotland. It will explore linkages and outcomes, fostering informed dialogue between disciplines and scales in the energy-policy-environment nexus. It is felt to be of strong relevance to sustainable renewable energy and integrative water resource decision making.

4.2 EARLY RENEWABLES IN THE UK AND SCOTLAND

Due to its location, topography and climate, the UK and Scotland have some of the best renewable energy resources in Europe (DECC, 2012a). Yet in the early 1990s, the UK was characterised as having 'negligible' renewable generation on a European scale (EC, 1994), due to planning barriers, a lack of political will and ineffective support mechanisms (Connor, 2003). At this time the vast majority of renewable electricity, and overall renewable energy generation came from public hydropower schemes in Scotland developed earlier in the 20th Century (Smith and Watson, 2002).

Following the Foyers scheme in 1896, the first main construction phase for hydropower in Scotland was to support the emerging aluminium smelting industry under the British Aluminium Company in the 1920s. Schemes such as Kinlochleven (24MW) and Lochaber (64MW) focussed on meeting these high energy needs by having large storage reservoirs fed by significant hydrological alteration, maximising output and reducing cost per unit of power. A load factor up to 80% (Payne, 1988) indicates a dependable, continuous generation and release profile, and there was often little provision for environmental flow management (Reid, 2002).

Large storage capacity and highly modified hydrological regimes were also characteristic of schemes in the second, but sustained and much larger nationalised construction phase from 1950 to 1965, under the North of Scotland Hydro Electric Board (NoSHEB). The hydrological influence of these schemes is significant, with complex abstraction often diverting the maximum quantity of water from surrounding catchments, and including only a simplistic approach to compensatory flows (Black et al., 2006). The development period delivered by NoSHEB was laid down in law through the Hydro-Electric Development (Scotland) Act 1943. It set out fairly open ended goals of the development of the water power resources of the Highlands of Scotland, and through distribution networks to support the wider welfare needs of economic development and social improvement of the Highlands (Payne, 1988). The result was a large scale development program that sought to maximise hydropower returns from the Highlands, with peak demand load sites in the south with modest reservoirs, near the industrial belt, and larger storage schemes in the north (Johnson, 1994).

4.2.1 A changing context for hydropower

The sustainability outcomes and downstream ecological trade-offs from hydropower are very much shaped by local hydrological and siting conditions (e.g. Gilvear et al., 2001; Marsh and Anderson, 2001) and the mitigation and compensatory flows applied (e.g. Black et al., 2006; Reid et al., 2004; Reid, 2002). However, this study will consider how the design and operation characteristics (Petts, 1984) are potentially shaped through incentive mechanisms, in turn influencing the sustainability challenges and the 'footprint' presented by hydropower at a scheme or national level in Scotland.

This research will examine the emergence and evolution of renewable incentive mechanisms in Scotland and investigate their potential to shape the trade-offs presented by hydropower. It will consider the three large incentive mechanisms; the Scottish Renewables Obligation (SRO) (1994), the Renewable Obligation (Scotland) (RO) (2002), and Feed in Tariffs (FiTs) (2010).

This chapter will firstly examine each of the three mechanisms, presenting an assessment of their implications for hydropower in Scotland. It will then provide a comparison of their differing approach, emphasis and mechanisms for incentivising hydropower. The influence on sustainability aspects will be considered, including outcomes for scheme characteristics, and implications on generational, regulatory, and strategic aspects.

It is suggested here that whilst incentive mechanisms may be important, they are one of many influential factors shaping the characteristics and implications of hydropower. However, with incentives reflecting an often changing wider energy policy approach, and often receiving media attention in terms of their costs to customers through rising energy bills, this chapter offers a worthwhile and innovative perspective to examine how specific energy policies shape hydropower sustainability at multiple scales.

4.3 THE SCOTTISH RENEWABLES OBLIGATION (SRO) (1994)

Up until the late 1980s the scope of policy commitment to renewables in the UK was restricted to research and development funding. Following privatisation of the electricity generation and distribution industries, however, subsequent support mechanisms sought primarily to develop the market for renewables and bring their costs down (Mitchell, 1995). The UK Electricity Act 1989 brought about the privatisation of the electricity industry in England and Wales; in addition it introduced the Non-Fossil Fuel Obligation (NFFO). Scotland followed suit with privatisation in 1991, and the establishment of a similar mechanism to the NFFO, the Scottish Renewables Obligation (SRO).

The SRO was established to drive down generation costs and give renewables a foothold in the electricity market by requiring public electricity suppliers to contract a certain percentage of their generating capacity from renewables. The SRO required developers of potential renewable schemes to submit a competitive bid proposal to supply electricity stating a price (in p/kWh) at which they would operate their schemes. Successful contracts would then be awarded on this basis. In Scotland there were three SRO rounds, enabled through Ministerial 'Orders' in 1994, 1997 and 1999. These set out the awarded contracts stipulating the developer, site and technology to be used. Over 32MW of hydropower generation capacity was contracted through this scheme in Scotland over its lifetime (NFPA, 2011), though in reality much less was actually constructed and became operational.

Through the SRO, Ministers were able to be very prescriptive about the schemes that were supported through the mechanism. As a result, each Order agreement varies in the total capacity contracted and the contribution from each technology, reflecting changing policy goals and market outlook (Harrison, 2005). The agreed electricity provided by generators to suppliers was at an above market price, with the difference funded by the Fossil Fuel Levy.

4.3.1 Hydropower characteristics under the SRO

Around 80% of hydropower schemes contracted under the SRO were expected to be constructed and become operational (OFFER, 1994). However this figure was much lower, with only 33% of the 32MW contracted being constructed (NFPA, 2011) due to planning, connection and environmental considerations as with the NFFO (Harrison, 2005).

Contract Name	Contracted Capacity (MW)	Tranche	OS Ref	Location
Beochlich	1.0	SRO1	NN 006 155	Argyll
Stanley Mills Hydro	1.0	SRO1	NO 114 328	Perthshire
Loch Poll	0.2	SRO1	NC 102 329	Sutherland
River Cuileig	3.0	SRO1	NH 191 788	Ross & Cromarty
Duror	0.7	SRO1	NN 003 550	Inverness-shire
Garrogie	1.9	SRO1	NH 494 144	Fort Augustus
Garry Gualach	0.8	SRO1	NH 170 003	Inverness-shire
Auchtertyre	0.6	SRO1	NN 354 292	Stirlingshire
Little Wyvis	0.6	SRO2	NH 458 608	Ross-Shire
Glen Tarbet	0.8	SRO2	NM 851 609	Inverness-shire

Table 4.0: Hydropower schemes constructed under the SRO (NFPA, 2011)

The ten SRO hydropower schemes that did become operational, totalling just over 10MW (**Table 4.0**), were mostly run of river in design, so would not have a prescribed generation and release approach associated with a storage scheme. An assessment of the potential influence the SRO had in shaping scheme characteristics is provided in the comparative section (**Section 4.6** below) , following an overview of the Renewables Obligation (Scotland) (**Section 4.4**) and Feed in Tariffs (FiTs) (**Section 4.5**).

4.3.2 The Garrogie scheme

One example of a hydropower scheme supported under the SRO mechanism is the 1.9MW Garrogie scheme on the River Fechlin. Although contracted through SRO1 in 1994, the scheme received the necessary regulatory and planning consent only in 2003. The Garrogie scheme is a run of river scheme located at the higher reaches of the River Fechlin, about 0.75km downstream of its inception at the northern end of Loch Killin. The River Fechlin is in the Northern Scottish Highlands, just to the east of Loch Ness. It flows north-west from Loch Killin to join Allt Brineag, after which it becomes the River Foyers and joins Loch Ness on its south side. It has a steep sided river valley, mostly enclosed within woodland cover on each bank. Impoundment and abstraction through a weir intake diverts a portion of the flow through a 2.5km buried pipeline, and returns it to the river channel through an outfall and powerhouse, creating a depleted reach of approximately 2.75km.

In addition to the Garrogie scheme, lower stretches of the River Fechlin also have been heavily influenced by hydropower infrastructure for some time, namely for the Foyers Falls scheme (1968) and the Foyers pumped storage scheme (1974). Abstraction here occurs at an intake at NH 496 143, which transfers water to Loch Mhor for storage and use in the Foyers pumped storage scheme. In lower reaches, on what is then the River Foyers, an additional abstraction at NH499 199 feeds the Foyers Falls conventional hydro scheme.

Under Scotland's River Basin Management Plan (RBMP), approved by Ministers in December 2009, the River Fechlin is covered by water body data sheets that contain summary information on river classification and objectives. The higher reaches of the Fechlin, upstream of the Foyers abstraction sites, were classified in 2008 as having a Bad overall ecological status, and, designated as a Heavily Modified Water Body (HMWB), having a Good ecological potential (SEPA, 2008). As a designated HMWB, due to the influence of the Garrogie scheme, it is able to satisfy WFD requirements by maintaining Good ecological potential over future river basin planning cycles through continued use of mitigation and management best practice. Nevertheless, the water body is classified as Bad in hydromorphology, hydrology and hydrology (abstraction) parameters. Reported pressures on the water body are flow regulation and abstraction from hydropower production through the Garrogie scheme.

As a 'Controlled Activity' under The Water Environment and Water (Scotland) Services Act 2003, the Garrogie scheme is licensed through the Water Environment (Controlled Activities) (Scotland) Regulations 2005 (CAR). The Garrogie CAR water use licence (Licence number CAR/L/1012161) details conditions relating, for example, to data reporting, sediment management, and, flow abstraction and management.

The licence details that:

- The maximum abstraction rate per *second* shall be 5.5m^3/sec at Point A (The weir)
- The maximum abstraction rate per *day* shall be 475200 m^3/day at Point A
- The abstraction shall not cause the flow in the River Fechlin to fall below 0.4 m^3/sec

Flow mitigation for the scheme therefore takes the form of maximum abstraction rates, per second and per day, and a 'hands off' flow for the water body. This maintained flow does not mandate specific seasonal provisions, as can be the case, for example, in water bodies where migratory species are present.

4.3.2.1 Garrogie application considerations

Although contracted through SRO1 in 1994, the Garrogie scheme only received planning (S57) and electricity generation (S36) consent by Scottish Ministers in 2003, after submission by Innogy plc (Npower) in November 2001, amended in 2002. The Highland Council, the relevant planning authority, considered a range of issues relating to ecology, hydrology, archaeology, landscape and visual impact. It was noted from the Environmental Statement that the Fechlin is not a route for migratory fish (salmon and sea trout), and it was felt that maintenance of existing pools and an acceptable compensation flow should safeguard brown trout over the affected reaches. The Highland Council approved the scheme, concluding that it was a modest sized scheme, and there were limited hydrological, ecological and other long term impacts.

As regulator for natural and conservation heritage, Scottish Natural Heritage (SNH, 2001) advised that the development could disrupt two bat roosts (Daubentons) in two old birch trees that would be flooded as a result of the new intake weir site. Further potential disruption of otters was also identified, but the two issues were addressed through licenses under regulation 44(2)(e), in the Conservation (Natural Habitats, etc.) Regulations 1994, that allows for the disturbance under a public and economic benefit. Although there were further concerns for potential impacts on birds (Merlin, Schedule 1, Wildlife and Countryside Act 1981) and landscape, the scheme did not fall within a national Scenic Area or designated Landscape or Historic Garden, SNH felt that these could also be overcome with sufficient mitigation conditions.

The Scottish Environment Protection Agency (SEPA, 2002) also commented on issues of hydrology, river morphology, pollution control and the EU Water Framework Directive (2000/60/EC) that was then yet to be transposed into Scottish law. SEPA felt that the proposed abstraction would result in a significant change to the hydrological characteristics of the river, so steps must be taken to maintain sufficient flow in the river to mitigate morphology and ecological impacts. The removal of gravel trapped by the intake weir was mandated as a precautionary measure to avoid any morphological implications. The creation of a depleted reach downstream of the intake was felt to be of hydrological significance, but due to the physical nature of the water course it was felt to be unlikely to be of adverse impact on aquatic ecology.

The potential implications for the River Fechlin were considered by SEPA in light of the WFD, as it was soon to become a central pillar to water governance in Scotland and the UK. It was SEPA's opinion at the time that the Fechlin was of High ecological status, though this designation was contested by the applicants. It is interesting to consider that this stretch of the Fechlin is now classified as Bad overall ecological status due to the pressures from hydropower flow alteration and abstraction (SEPA, 2008). However this derogation of status is still permissible under the WFD, where appropriate levels of mitigation are applied to HMWB that provide socio-economic benefits, and Good ecological potential only has to be maintained.

In their advisory role to Scottish Ministers, the Fisheries Committee (2003) felt that the intake siting may have impacts on arctic char and trout that might spawn in the upper Fechlin. It was agreed that the intake would be sited further downstream, reducing the risk to fish migrating between the upper Fechlin and the Garbh-bhac, and to any Loch Killin trout and charr that might spawn in the upper Fechlin.

In making their decision, Scottish Ministers considered these representations and issues relating to the application. They judged, however that following the application of appropriate mitigation measures, the remaining adverse effects of the scheme would not be significant enough for consents to be refused (Scottish Government, 2003). Although one of the larger SRO hydropower schemes, the magnitude of any adverse environmental impacts associated with Garrogie are seen to be small and easily overcome by a number of mitigation conditions. Located within a relatively enclosed river valley, with limited hydrological, ecological or long term sustainability impacts, it offers an example of a fairly large run of river scheme with manageable and acceptable trade-offs. The sustainability considerations for Garrogie are typical for a run of river scheme of this size, and at 1.9 MW it offers high environmental 'efficiency', in terms of making a significant contribution to national Scottish Government targets, whilst minimising impacts (SEPA, 2010b), making the alterations to the water environment 'justifiable' (i.e. Scottish Government, 2010).

4.4 RENEWABLES OBLIGATION (SCOTLAND)

Replacing the NFFO and SRO, the Renewables Obligation (RO) and Renewables Obligation (Scotland) (RO(S)) are the second generation of renewable incentives frameworks, established in April 2002. The central aim of the RO and RO(S) is to maximise the level of market competition within the support mechanism, whilst also guaranteeing a minimum installation of national renewable capacity (Connor, 2003). The mechanism is currently the main framework for supporting the large scale deployment of renewable electricity in the UK. The RO and RO(S) place an obligation on licensed electricity suppliers in England, Wales and Scotland to source an increasing proportion of electricity from renewable sources. To demonstrate they have met their obligations, suppliers must accrue a corresponding amount of 'green certificates' (ROCs) which are made available from eligible generators for units of renewable energy produced.

The initial approach for the mechanism, however, was to be technologically neutral, as the Department of Trade and Industry (DTI) felt at the time that they should not dictate the relative importance of each technology, as it would 'introduce artificial distortions into the marketplace' (DTI, 2001, p.3). This model, however, created a single market for all technology types, leading to already established and mature technologies (e.g. onshore wind) becoming even more attractive as they were cheaper, whereas other emergent technologies (e.g. offshore wind) became uncompetitive, stifling innovation (Foxon et al., 2005).

The RO and RO(S) were subsequently reformed in 2007, outlined through the 'White Paper on Energy: Meeting the Energy Challenge' (DTI, 2007), with different levels of support for technologies. It was projected that otherwise the renewable electricity contribution targets for 2010 (10%), 2015 (15%) and 2020 (30-35%) would not be met (Wood and Dow, 2011). Although a market based mechanism, the mechanism permits a considerable amount of government intervention through the incremental increase of the national generation percentage target, or changes in the ROC buy-out price, allowing for changing political and policy considerations (Connor, 2003). This was especially the case post-2007, with technologies receiving differing and changeable levels of financial support (i.e. ROCs awarded per MWh of generation). The characteristics and effectiveness of the initial and reformed RO are well documented (i.e. Mitchel and Connor, 2004; Mitchell et al., 2006; Wood and Dow, 2011). This investigation, however, specifically seeks to identify how the mechanism in

Scotland has shaped the characteristics and challenges of hydropower at a scheme and national level.

4.4.1 Hydropower characteristics under the RO(S)

From the outset, hydropower was fairly competitive under the RO as even without banding it was an established 'near-market' technology so it was more favourable against emerging technologies, as with onshore wind (Foxon et al., 2005). From 2007 ROC weighting for hydropower in Scotland has remained constant with 1 ROC for every MWh of generation, despite a proposal to reduce it to 0.5 ROC/MWh from April 2013 (Scottish Government, 2011a) similar to 0.7 ROC/ MWh in England and Wales (DECC, 2012c), to focus weighting towards emerging marine and offshore technologies. Whilst banding levels are reviewed every four years to ensure the appropriate relative levels of support by technology, existing generating stations already accredited under the scheme keep the old banding level.

Unlike with the NFFO and SRO that contract a limited number of schemes directly, the RO creates a market within which eligible schemes may operate, with developers using ROC weighting as part of scheme scoping and viability. The mechanism grants eligibility through three avenues:

- Micro hydro (i.e. <1.25MW capacity) (From 2012, schemes under 5MW operate under FITs)
- Small hydro (i.e. <20MW capacity), constructed or 'renewed' since 1990
- Large hydro (>20MW)

Existing schemes are therefore eligible for ROCs, in particular schemes older than 1990 if they have had main components renewed since that date (i.e. turbine blades or inlet nozzle). Examining the characteristics of hydropower under the RO is therefore more challenging, as there is a variety of ways in which the eligibility criteria can be met, leading to a variety of scheme types and environmental outcomes.

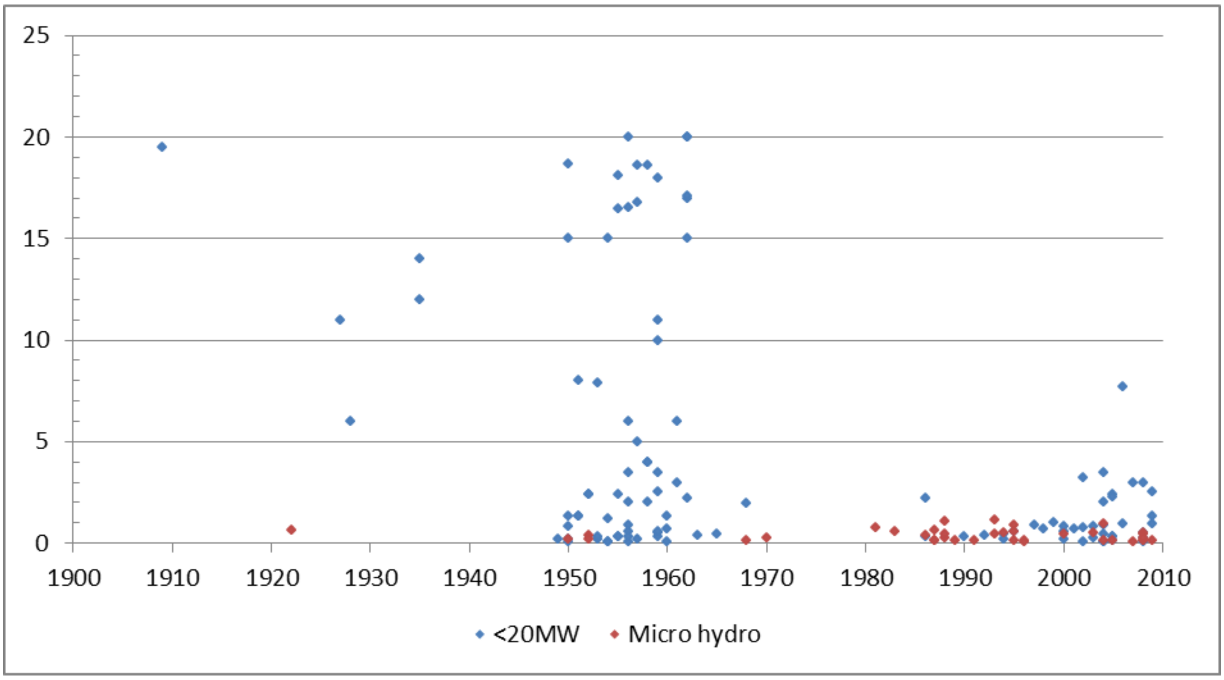


Figure 4.0: Capacity (MW) of hydropower operating under the Renewables Obligation (Scotland) (Ofgem, 2013)

All accredited hydropower stations under the RO(S) are shown in **Figure 4.0** showing their capacity and construction date (excluding Glendoe at 100MW, operational in 2008). Due to the eligibility criteria, there is diversity in scheme size and construction date, but this pattern mostly reflects the historical development of hydropower in Scotland.

Given the above eligibility criteria, those schemes that operate under the RO(S) mechanism appear to fall into a number of groups, namely:

i) renewed, sometimes large historical schemes such as Kilmorack (20MW) and Invergarry (20MW);
ii) more recent (post-1990) run of river schemes that perhaps used to operate under the SRO, such as Beochlich (1MW) and River Cuileig (3.2MW);

iii) new schemes such as at Culligran CS (2MW)and Fasnakyle CS (8MW) that operate on the compensation flow of existing larger storage schemes, and finally;

iv) fully new 'stand-alone' run of river schemes such as River E (3MW) and Douglas Water (3MW), with the 100MW Glendoe storage scheme the exception to this.

This study seeks to examine how the various incentive mechanisms have shaped the contribution and characteristics of hydropower in Scotland, whilst also considering the potential effect on scheme level operational dynamics and approach. Against this diversity of scheme types under the RO(S), it is as such important to consider both 'new' schemes constructed post-2002 when the RO(S) was brought in, and also 'renewed' existing schemes.

4.4.1.1 New schemes under the RO(S)

The advent of the RO(S) brought about a new wave of hydro construction in Scotland and, as shown in **Figure 4.0**, these post 2002 schemes were slightly larger in capacity than the preceding schemes. **Figure 4.1** shows more clearly the distribution of new scheme by size constructed under the RO(S), this time removing the delayed SRO schemes such as River Cuileig and Garry Gualach which were conceived under the SRO but now operate under the RO(S). Averaging 1MW when discounting the exceptional 100MW Glendoe scheme, **Figure 4.1** conveys the variability in scheme size under the RO(S), reflecting the differences in scheme type.

Examples of new stand-alone schemes include the larger run of river Douglas Water (3MW), and the conventional Kingairloch (3.5MW) that dammed Loch Uisge raising the level by nine feet. At the time, Kingairloch was the largest conventional storage hydropower scheme constructed in the UK since 1963 (IWPDC, 2005). Other new build under the RO(S) were much smaller, such as the 450kW Cleghorn Bridge run of river scheme that reused an existing weir and turbine house dating back to the 1800s, and cleaned up much of the historical industrial pollution at the site.

In parallel to the emergence and development of energy policy and incentives, the regulation of water resources in Scotland has experienced change under the Water Framework Directive (2000/60/EC) and the Water Environment (Controlled Activities) ('CAR') Regulations (2005). One key outcome is that existing schemes' water use licences are increasingly being revised to bring them up to date with present objectives and needs, to deliver improvements in affected water bodies (e.g. Tummel (CAR/L/1011485), Conon (CAR/L/1011464), and Ness (CAR/L/1011471)).

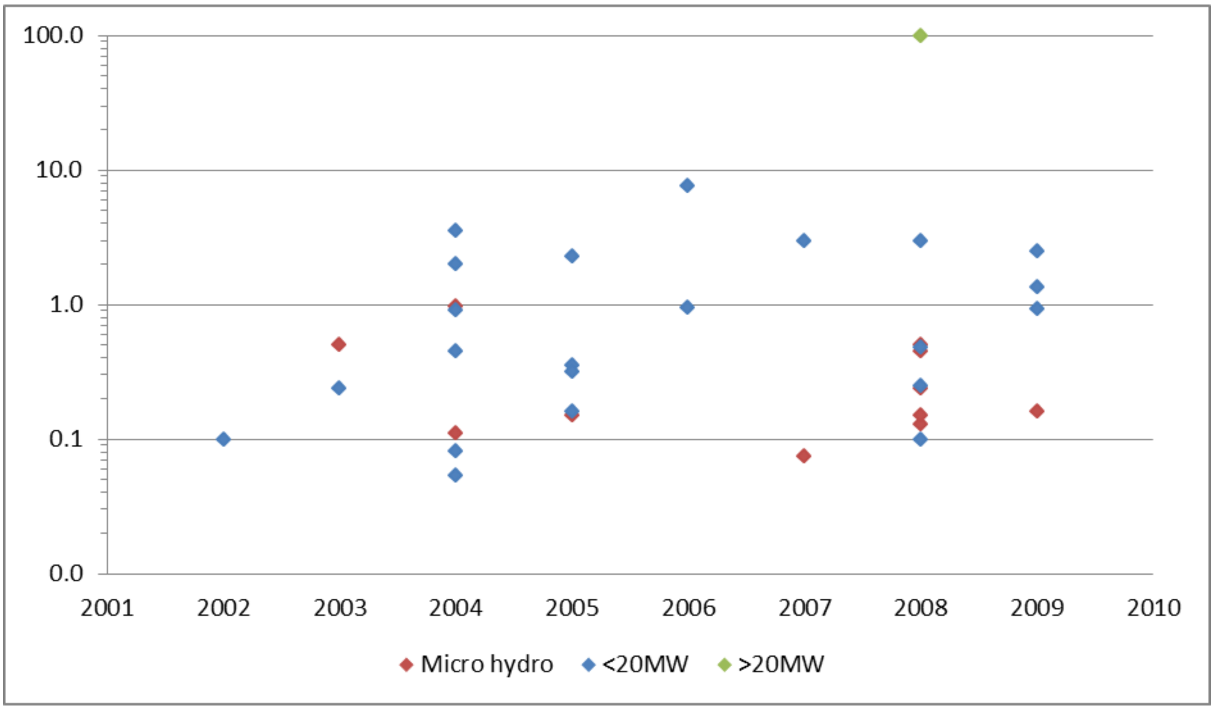


Figure 4.1: Capacity (MW) of new hydropower schemes operational under the RO(S) constructed by year since 2002 (Ofgem, 2013)

With SEPA undertaking this programme to reinforce environmental flow releases and altering the way in which large storage schemes manage water, there can be reductions in the volume that can be used for generation. Against this development, the RO(S) has inadvertently provided an avenue for generators to regain generation capacity and income by supporting schemes that generate using the compensation flows of larger historical storage schemes. For example, completed in 2005, the Fasnakyle Compensation Set (8MW) added a fourth turbine to the site of the existing 69MW Fasnakyle power station that was constructed in 1951 and forms a central part to the Affric-Beauly

NoSHEB scheme, fed by the Loch Benevean dam. The Fasnakyle CS generates continuously on the station's compensation water flow (Belfour Beatty, 2012), and is ROC eligible.

4.4.1.2 Renewed schemes under the RO(S)

With RO(S) eligibility extending to schemes up to 20MW that have been 'renewed' since 1990, **Figure 4.0** also shows that many existing and historical schemes operate with ROCs under this route. It appears from **Figure 4.0** that the 20MW upper limit does result in a somewhat artificial threshold, with a number of schemes up against this limit, such as Kilmorack (20MW), Invergarry (20MW) and Aigas (20MW). This threshold excludes many stations from this 1960s development period from the mechanism, such as Inverawe (25MW), under Sloy-Awe scheme near Loch Lomond, and Deanie (38MW) from the Affric-Beauly west Highland development.

With the majority of current RO(S) hydropower capacity, some 364MW, delivered by renewed schemes (see **Figure 4.2**), the 'renewal' avenue for eligibility plays a significant role in delivering on the RO(S) aims and underpinning the operational capacity under it. It is suggested here that this basis for criteria has, alongside other factors such as the regulatory changes touched upon earlier, supported a move for many large historic schemes to undergo significant renovation and refurbishment.

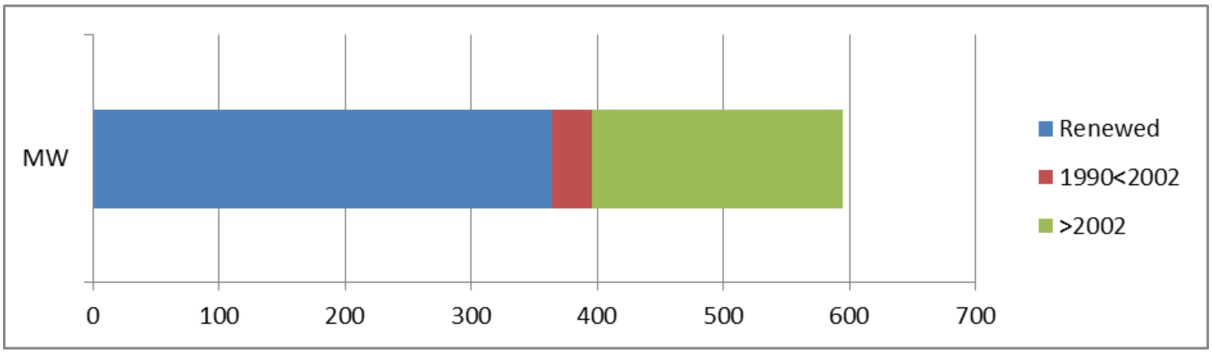


Figure 4.2: Current RO(S) eligibility breakdown by type (MW) (Ofgem, 2013)

Operating the majority of the public 20th century NoSHEB schemes following privatisation, SSE have an on-going and ambitious refurbishment programme involving many hydropower stations throughout Scotland. In addition to the 2MW of compensation set capacity added in 2004, the Culligran power station (17MW) downstream of Loch Beannacharan on the River Farr, underwent a large refurbishment under the programme in 2005. The Culligran renovation had the stated goals of extending the operational lifetime of the scheme; improving its efficiency, output and environmental performance, and; to reduce the need for future maintenance. It involved the refurbishment of the 17.1MW Deriaz turbine and secondary 2MW Frances turbine, as well as refurbishment of the primary and secondary generators. The introduction of a digitally controlled governor to the main unit was also made, enabling improved adjustment of load so the generator always turns at the correct speed (van Rooy, 2006). This scheme is an example of how although being constructed in 1962, it is now eligible for ROCs due to having a capacity under 20MW, and as its main components were renewed after 1990.

However it is also the case that the Scottish Government was aware of 10 hydropower schemes including Kinlochleven that were down-rated in capacity to below 20MW between 1999 and 2002 to qualify for support under the RO(S) (SPICe, 2008). On face value, this presents a perverse outcome for the RO(S) as the eligibility criteria has caused a reduction in the installed capacity of renewable schemes. It is argued however that in these instances although leading to a reduction in capacity, support under the RO(S) led in fact to increased output through more efficient turbines, and an extension to the operational lifetime of schemes due to financing refurbishment (Scottish Government, 2008). As such, this dynamic presents an interesting and complex interplay of sustainability challenges and potential synergies, which could form the basis of future research. It is an acute example however of the way in which the eligibility criteria of an incentive mechanism can influence and interact with wider elements of sustainability.

The implications of these ROC eligibility criteria for hydropower sustainability will be discussed more fully in the comparative section of this chapter.

Unlike the SRO, the RO(S) is open to market conditions, with variability in both electricity and ROC price. As demonstrated by the uniqueness of Glendoe, however, this has not led to a surge in development of peaking, price led schemes due to the importance of other factors, such as site availability, and environmental and landscape issues. Indeed, in recent UK and Scottish energy policy documents it is commonly stated that future hydropower deployment potential is likely to be mostly small run of river schemes, with further large storage schemes unlikely due to site availability and environmental considerations (e.g. AEA, 2010; DECC, 2011b; Scottish Government, 2011)

4.4.1.3 The case of Glendoe

Operational in 2008, Glendoe is a large (100MW) high profile conventional hydropower scheme in the Monadhliath mountains, to the south east of Fort Augustus, overlooking Loch Ness. With a 35m high dam and over 18km of tunnelling and transfer aqueducts, creating a reservoir catchment of 75km^2 and an operational head of over 600m, it is the largest conventional storage scheme to be built in over 40 years.

As the RO(S) was being brought in, SSE revisited many of the potential sites that were identified, but not developed under the NoSHEB constructional period, and applied current environmental, planning and construction criteria. Considered the only viable site from amongst those revisited, a range of potential scheme options presented themselves for Glendoe including the 100MW option taken, a sub-10MW run of river scheme and a pump storage scheme. Smaller schemes were, however, discounted due to the larger infrastructure costs needed, and pumped storage was considered less viable due to a costly head-distance ratio, but also because a pumped storage scheme would not be ROC eligible (Seaton and Hobson, 2005).

Hydropower schemes that can provide peaking power are of raised value to the national grid, as they are able to deliver quick response, flexible, demand targeted generation (National Grid, 2012). Both conventional-peaking such as Glendoe and pumped storage schemes like Cruachan are able to perform this role albeit in slightly different ways, but result in significantly different challenges and implications for sustainable water resource management. In the case of Glendoe, ensuring the scheme was RO(S) eligible was a key determinant for the resulting scheme characteristics, and in turn the associated hydrological implications.

4.4.2 Hydropower generation under the RO(S)

Under the mechanism ROCs are initially issued monthly to accredited generators by Ofgem, in amounts determined by the net amount of renewable electricity they produce. This arrangement means that the amount of ROCs in the market mostly reflects the amount of renewable output under the scheme. ROCs can then be sold directly or indirectly to suppliers, who are required to present sufficient certificates to cover their obligations for a 12-month compliance period (financial year). Any shortfall in ROCs can be made up by paying a fixed base amount into a 'buy-out' fund (Ofgem, 2011a).

The ROCs themselves are usually bought by suppliers in addition to electricity via a power purchase agreement, and with the ROC market value varying with the balance of supply and demand (Harrison, 2005), leaving the potential for fluctuations at the start and end of the compliance period. With this large variety in scheme capacity, design and generation type under the RO(S) it is challenging to identify if the mechanism has a widespread feedback to affect the operational characteristics or approaches of the schemes themselves.

The Ofgem (2013) Renewables Register provides an online public portal for ROC data, which feeds into the monitoring and reporting of the mechanism by Ofgem. As this research project could not obtain detailed data on generation and what can be often sensitive commercial information from generators themselves, this public register provides some value to this investigation. Whilst it does display ROCs awarded per month, by technology, it unfortunately does not distinguish between the constituent UK countries, but takes the mechanism as a whole.

Figure 4.3 shows that under the (UK wide) RO there is monthly variability in ROCs awarded by technology. Specifically driven by wind output, and in line with the seasonal electricity demand of the UK (National Grid, 2012), there appears to be a pattern for ROCs to peak in the winter months, but with further fluctuations often due to drops in wind yield (Ofgem, 2012). The growth in wind output from raised overall capacity is also shown here.

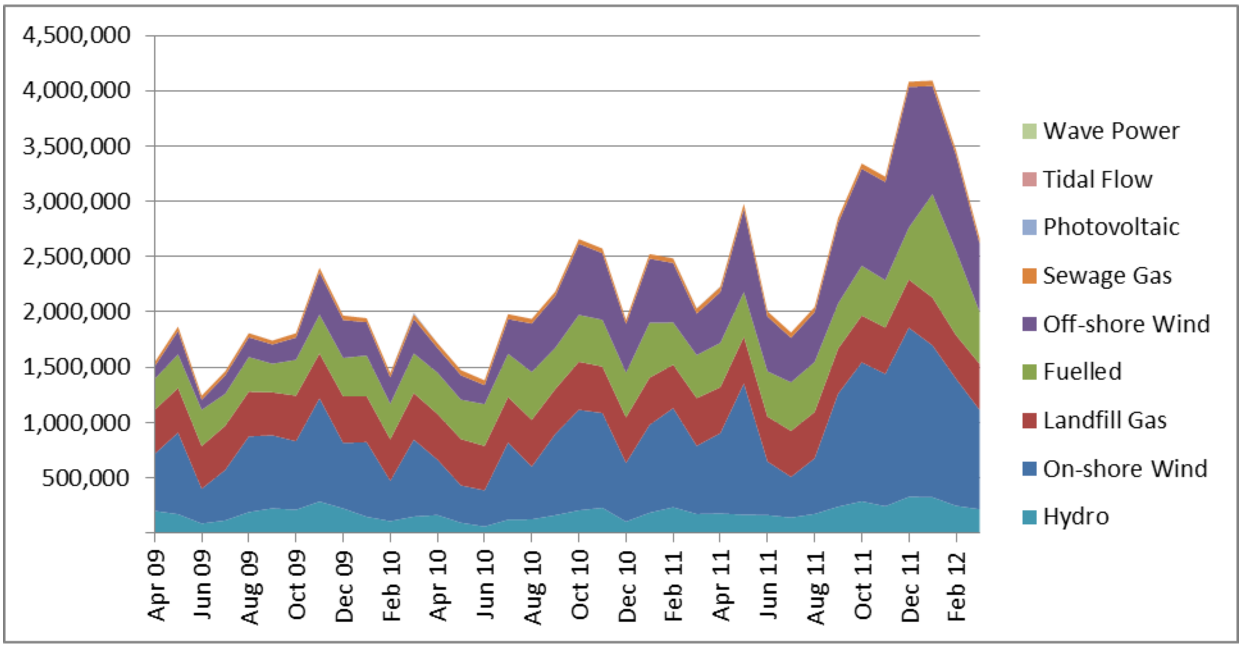


Figure 4.3: ROCs awarded per month, by technology since 09/10 compliance period (Ofgem, 2013)

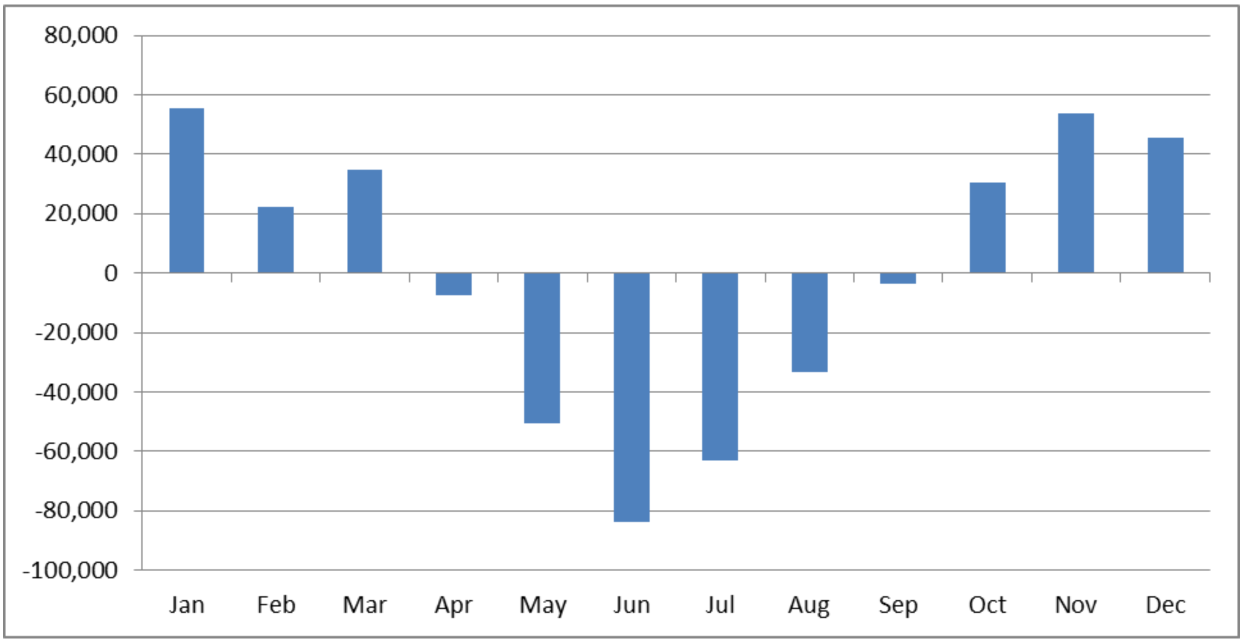


Figure 4.4: Average hydropower ROCs awarded per month, compared against the long term monthly average (compliance periods 2007/08 to 2011/12) (Ofgem, 2013)

In the 2010-11 compliance period, Scottish hydropower accounted for 90% of the UK total ROCs awarded for the technology, with 1.65 million of 1.85 million (Ofgem, 2012). Therefore, despite the Ofgem Register not distinguishing by country as in **Figure 4.3**, it is felt that Scottish specific trends can be taken from the wider UK data for hydropower.

Taking the average ROCs awarded for hydropower generation per month from the compliance periods 2007/8 to 2011/12, and comparing them to the long term monthly average for the same period, **Figure 4.4** shows the generation pattern for hydropower under the RO. It shows the distinct seasonality to ROCs awarded, and therefore generation, with months April to September at below average and October to March above the average.

With hydropower output tied to water availability, the principal reason for this distribution is that higher seasonal rainfall magnitudes can support increased generation. In this scenario, storage and run of river schemes alike are able to operate at a higher load, due to the plentiful supply of water. With the RO being open to market forces, however, electricity value fluctuates along with ROC value (Harrison, 2005). It follows that with winter months offering greater demand magnitudes (National

Grid, 2012), there is a greater scope for overall increased generation, and potentially raised peaking generation to target this need.

Figure 4.4 shows a clear seasonality to hydropower ROC and generation output. However it is not possible to determine here if this is due principally to the increased rainfall and generational potential in winter months, or the increased seasonal demand and price return. In reality, the trend is most likely due to a combination of both factors, with individual schemes responding differently throughout the year depending on their characteristics. For example at higher flow magnitudes, the Douglas Water (3MW) run of river scheme will abstract a greater volume of flow over the compensation flow minimum, but it will not be able to otherwise target daily or seasonal generational demand periods for greater economic return. On the other hand, whilst fairly exceptional as a new peaking scheme, Glendoe (100MW) is able to target peak demand periods with flexible generation, but also can benefit from greater resource availability due to this and its storage capacity.

It was initially also hypothesised that the financial year compliance periods for the RO(S) may create a further artificial seasonality to the distribution of ROCs and generation, as suppliers look to ensure they fulfil their obligations before the cut off, resulting in raised generation in March. However, **Figure 4.4** does not support a widespread occurrence of this. Nevertheless overall, as the RO(S) is structured to allow for the influence of market conditions, both with electricity and ROCs, it creates conditions where hydropower, as a more flexible renewable technology (i.e. over wind which is purely driven by resource availability), can maximise its contribution and return. But ultimately, due to the variety of schemes under the RO(S), from the renewed large NoSHEB baseload or peaking stations, to the more recent run of river schemes, there is not the widespread operational flexibility for the ROC output profile to change dramatically, even though the RO(S) may seem to create the conditions to support it.

4.5 FEED IN TARIFFS (FITs)

In 2010, the UK government brought in a mechanism of Feed in Tariffs (FITs), designed to incentivise and encourage small-scale renewable generation (<5MW), particularly in organisations, businesses and communities who would not normally operate in the electricity market. FiTs compliment the UK (DECC, 2011b) and Scottish (Scottish Government, 2011) targeted plan of action to deliver large scale renewables for commitments under the 2009 Renewable Energy Directive, by promoting take up of small-scale, low-carbon technologies by the public and communities. The FiTs scheme aims to:

i) Empower people and give them a direct stake in the transition to a low-carbon economy;

ii) Help develop a supply chain that offers households a wide range of cost-effective measures to lower their energy use and carbon emissions; and

iii) Assist in the public take-up of carbon reduction measures, particularly measures to improve the energy efficiency of buildings

Catering for small, non-traditional generators, installations are allocated an appropriate tariff based on scheme size and technology. Licensed Electricity Suppliers pay installations a Generation tariff for every metered kWh generated and used on site, and an Export tariff available at a fixed amount for electricity exported back to the network. Sites benefit financially through the generation tariff return, any additional income from the export tariff, and the reduced dependency on grid electricity.

The FITs policies and specific tariff rates are set by the Department of Energy and Climate Change (DECC), but the scheme itself is administered by suppliers and Ofgem. FiTs replaces the RO as the main mechanism of support for hydro under 50kW, and 50kW to 5MW schemes are given a one off choice of operating under FiTs or the RO. The scheme has meant that existing small-scale generation operating under the RO has to be transferred over to FITs (DECC, 2010).

An installation will receive the tariff rate on the basis of technology, capacity and date of installation. The standardised export tariff is much lower than the generation tariff as a way of incentivising the use of energy onsite, making the scheme more like a production tariff than a typical feed in tariff. Once a year, however, generators are entitled to choose to 'opt-out' of the fixed export tariff and try to negotiate a better rate with the electricity supplier (DECC, 2010).

Following a review of solar photovoltaic weighting in 2011, in February 2012 DECC (2012b) undertook a comprehensive review of FiTs addressing scheme administration issues, but also as with the RO, making adjustments to tariff weighting reflecting policy and uptake trends to ensure value for money. The 2012 FiTs review included an assessment of the hydro tariffs in light of the then on-going UK wide changes to ROC weighting, so as to avoid perverse incentives to choose one instrument over the other, or to undersize projects to obtain an overpriced FiTs tariff (DECC, 2012c). The FiTs consultation proposed to keep 2-5MW installations at 4.5p/kWh, the equivalent of 1ROC/MWh, but if the RO review went down to 0.5ROC/MWh then this would mean a further reduction in FiTs accordingly to 2.3p/kWh. As we have seen, the RO in England and Wales went down to 0.7ROC/MWh (DECC, 2012c), but Scotland stayed at 1ROC/MWh, so the FiTs levels for the highest capacity band have been adjusted as such.

Tariff/ Year	>Dec 2012	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20
<15kW	21.00	21.00	19.95	18.95	18.00	17.10	16.25	15.44
15kW < 100kW	19.70	19.70	18.72	17.78	16.89	16.05	15.24	14.48
100kW <500kW	15.50	15.50	14.73	13.99	13.29	12.62	11.99	11.39
500kW < 2MW	12.10	12.10	11.50	10.92	10.37	9.86	9.36	8.89
2MW < 5MW	4.48	Tariff set at RO equivalent						

Table 4.1: Hydropower tariffs under FiTs by capacity (DECC, 2012e) (Before RPI deductions)

As **Table 4.1** shows, the tariffs are subject to degression from 2014, at approximately 5% a year to reflect the lowering of costs as installed capacity rises. DECC also added an additional tariff band at 100kW to 500kW, to aid intermediate investment in the previous 100kW to 2MW band. The smallest band was also capped at 21p/kWh after the review in line with other technologies.

4.5.1 Hydropower characteristics under FiTs

The hydropower schemes in Scotland operating under FiTs very much reflect the mechanism's orientation towards local, community level generation. **Table 4.2** shows that there are 352 FiTs hydropower schemes in Scotland, totaling just over 34MW in capacity, resulting in a small average installation of 97kW (0.09MW). **Table 4.2** also shows that average scheme capacity varies by generation category, which indicates the role and orientation of an installation. Here, although domestic schemes are most numerous, accounting for the majority of schemes (64%), they only contribute 2.6MW, some 7.5% of the total hydropower capacity under FiTs. The result is that since 2010 whilst there is an overall average capacity of 97kW, there is a large underlying uptake in predominately small capacity domestic hydropower schemes, with an average capacity of only 11.5kW.

	Domestic		Commercial		Industrial		Community		Total	
Technology	Schemes	MW	Schemes	MW	Schemes	MW	Schemes	MW	Schemes	MW
Anaerobic digestion	1	0.0	27	26.6	10	4.8	0	0.0	38	31.4
Hydropower	226	2.6	97	28.3	14	3.0	15	0.3	352	34.4
Micro CHP	429	0.4	2	0.0	0	0.0	1	0.0	432	0.4
PV	349,516	1,136.6	9,107	335.1	552	42.5	1,644	17.3	360,819	1,531.6
Wind	3,291	31.6	886	61.2	41	8.7	145	6.9	4,363	108.3
	353,463	1,171	10,119	451	617	59	1,805	25	**366,004**	**1,706.1**

Table 4.2: Renewable schemes and capacity by category under FiTs in Scotland (2010-2013) (Ofgem, 2013)

Although dwarfed by the uptake in PV under FiTs, being much less site dependent, the hydropower response to the mechanism in Scotland is dominated by small domestic, run of river schemes pitched at the highest tariff return of under 15kW. With eligibility only extending to new, or transferred recent RO(S) and non-pumping schemes under 5MW, and aimed at generation from non-traditional sectors, the mechanism is dominated by a fairly specific scheme type, albeit differing along with local site characteristics.

One typical micro-hydro run of river scheme operating under FiTs in Scotland is the 9kW domestic installation near Auldgirth, on the Auchenage Burn, a small tributory of the River Nith in Dumfries and Galloway, some 12 miles north of Dumfries. The scheme consists of one main screened abstraction weir on the (1 to 2.5m wide) Auchenage Burn, and a smaller secondary intake on an upstream tributary, forming approximately 1.72km^2 of drainage catchment. A 680m penstock runs overground conveying the abstracted flow through a wooded gorge before entering a small powerhouse, with an outlet after a short tailrace.

An objection to the scheme was made to the planning authority by the Nith District Salmon Fishery Board (NDSFB, 2009) on the basis of the potential damage to migratory fish. They described the development of hydropower on the tributaries of the Nith as in principle incompatible with the preservation and enhancement of spawning and nursery habitats. Due to being a micro-scheme on a previously undeveloped tributary, the site owners arranged a scoping inspection of Auchenage Burn to identify the baseline conditions for fish, namely spawning species. The inspection identified a large pile of debris and rubble through which the burn was percolating in its upstream reaches, presenting a clear upstream migratory limit. In adjacent downstream reaches there is considered to be little spawning or trout habitat, with predominantly boulders and exposed bedrock in the wooded gully. Further downstream as the burn leaves the gully and the gradient reduces, there are more opportunities for fish refuge and spawning, and habitat that could support a trout population. However the Auchenage Burn subsequently encounters a natural feature called The Gush, which is a completely impassable natural rock formation, creating an upstream limit to any potential migratory salmonids or lamprey coming up from the River Nith. Nevertheless, fish weir screening alongside the use of astroturf to aid the movement of eels was recommended and installed (Chrisholm, 2010). Additionally, whereas there was evidence of otters, no otter holts were found on Auchenage Burn, negating the need for a licence to disturb European Protected Species. Otter mitigation recommendations were made for the construction phase (Spray, 2009). Mitigation for the scheme consists of abstraction rate limits and hands-off flow, in addition to the screening of intake weirs (SEPA, 2010b), alongside the minimising of visual and landscape impacts through, for example, tree planting (M Aitken 2012, pers. comm 9 November).

4.6 COMPARING INCENTIVES

Renewable energy incentive mechanisms continue to play a significant role in delivering on Scottish and UK renewable generation targets and aspirations, and so they are a key feature supporting the transition to a low carbon economy. The differing structure and orientation of the mechanisms themselves contribute to shape the characteristics of hydropower in Scotland, and in this way influence the resulting regulatory challenges and sustainability outcomes at all scales.

Building from the above introduction to the SRO, RO(S) and FiTs mechanisms with reference to hydropower in Scotland, the following comparative analysis will consider the incentives together against a number of aspects, thereby to inform our understanding of their influence on issues of renewable energy sustainability. From this comparison, six outcomes will be generated as to the way in which incentive mechanisms affect issues of renewable energy sustainability for hydropower.

4.6.1 Scheme characteristics

The characteristics of hydropower schemes are an important determinant for the types and magnitude of environmental and downstream implications (Petts, 1984). However, rather than leading to a specific scheme type, there has been shown to be considerable variability under each incentive mechanism. This variability is in part due to aspects within the mechanism itself. In this respect it is a similar case with the RO(S) through its varied eligibility criteria, which allow for renewed historical storage schemes and new run of river alike, but also typical external forces such as site constraints and regulatory considerations.

With the NFFO and SRO contracts being awarded in technology bands through competitive bidding on generation costs, setting the fixed prices paid per KWh, there was considerable pressure on applicants to drive down the costs of their schemes (OFFER, 1994). This competitive bidding approach and the restricted number of schemes supported meant the system suited larger and more commercially secure developers who were able to obtain finance at a cheaper rate than smaller or new entrants (Mitchell, 1995).

Due to a number of external trends discussed previously, new hydropower in Scotland over the last 20 years is more likely to be in the form of run of river schemes. The overarching goal of the SRO to drive down the costs of renewable energy generation, reflected through the competitive bidding process used, reinforced this trend with the demanding financial criteria being more suited to smaller and efficient run of river schemes, over larger storage counterparts. Additionally, with generation returns based on a fixed price per kWh, there is no incentive to target demand peaks as the SRO schemes are insulated from market fluctuations, thus suiting the continuous baseload generation of run of river schemes, rather than storage-peaking orientated installations.

We have seen that the goals of FiTs to incentivise small-scale, community level, non-traditional generators has resulted in a surge in construction of domestic micro schemes that average 11.5kW, pitched to meet site and regulatory needs but also to come under the 15kW highest tariff rate. The sizing, regulatory constraints and need for affordability at this level mean that these schemes are commonly minimalist run of river, and located on private land, potentially on the upper reaches of previously undeveloped small burns feeding the tributaries of larger rivers. Furthermore, the RO(S) mechanism presents a greater diversity in the hydropower schemes that operate under it, due to the eligibility criteria allowing for schemes constructed or renewed since 1990. The wider capacity range supported (>5MW) giving scope for a number of scheme types is also a significant factor. As discussed, the outcome is that under RO(S) we see new ‘stand-alone’ medium sized run of river schemes such as Douglas Water (3MW), and the conventional Kingairloch (3.5MW), alongside compensation set schemes that work off the release profile of existing schemes such as at Fasnakyle. However as shown, the majority of RO(S) capacity is in the form of renewed existing schemes, which although capped at 20MW, are often larger, impoundment installations from the NoSHEB period. The occurrence of refurbished hydropower that was also down-rated presents a complex picture of schemes with reduced capacity, but potentially increased output and operational lifetime (Scottish Government, 2008).

4.6.2 Generational implications

In its simplest form, hydropower harnesses the natural flow of a river, creating hydrological alteration through abstraction or sometimes flow release profile, which reflects the generational approach of the scheme (Petts, 1984). Taking this principle, and the concept of reconciling the renewable energy benefits of hydropower with the tensions and trade-offs for river ecosystems (King and Brown, 2006; Reid et al., 2004), this investigation has sought to examine the role of incentive mechanisms in shaping generational, and consequently hydrological profiles from hydropower.

As touched upon above, taken in isolation, with the SRO creating generation isolated from market forces, awarding a fixed price per kWh, it would arguably result in a preference for baseload generation schemes, as there is no pressure to follow price fluctuations. In turn, were this the case, the associated hydrological implications would be more akin to moderated flow regimes, with a flatter flow duration curve (FDC) indicating less severe rates of change and channel narrowing and reduced lateral habitat connectivity downstream. In contrast to these characteristics, the RO(S) is more market driven, with both ROC and electricity price fluctuating with demand, meaning it is more suited to load following, flexible generation, resulting in more flashy, hydropeaking, with steeper FDC and rates of change, with habitat inundation and littoral species stranding.

This investigation, however, has highlighted that these incentives mechanisms do not exist in isolation, but are one of a whole host of issues and wider context that contribute towards shaping hydropower characteristics, operation, and sustainability challenges. What this discussion has highlighted is that in reality RO(S) schemes are constrained by site availability and suitability, and regulatory constraints, meaning that a lot of the new stand-alone schemes were run of river, so were not targeted or flexible generation. Again with FiTs, whilst there is the option to opt out and negotiate export tariffs with suppliers for a potentially higher return, the emphasis on domestic and community schemes means many would not seek to maximise profit in this way. There is in addition the fact that at this scale of capacity (<5MW) most schemes are low-head or run of river schemes anyway, so are more baseload orientated.

4.6.3 Regulatory implications

Hydropower presents a sector where the distinct areas of energy and environmental policy interact, resulting in regulatory implications and the need to reconcile potentially conflicting needs (Reid et al., 2004). However, consistent with the orientation of this thesis, this interaction is in itself dynamic, as both areas of governance are themselves developing and evolving independently. Furthermore, the hydropower agenda is often *energy led,* requiring a further associated response or adjustment from the environmental side.

As a renewable energy technology in Scotland, hydropower is in a unique position as it is subject to two separate environmental regulatory consents systems. Water activities that may affect Scotland's water environment are regulated and licenced by SEPA under the Water Framework Directive (2000/60/EC) transposed through the Water Environment (Controlled Activities) (Scotland) ("CAR") Regulations 2005. Additionally, hydropower is also subject to planning control through the local planning authority or Scottish Government, under which SNH has statutory responsibility for habitats, species and landscape issues, for example through the 'Habitats Regulations' (Habitats Directive 92/43/EEC, and Birds Directive 2009/147/EC).

At a scheme level, it is well reported that hydrological science often encounters change and uncertainties with aspects of water resource management (e.g. Werritty, 2002), leading to the need for an often responsive and adaptive approach utilising the precautionary principle for hydropower (e.g. Acreman et al., 2009). In addition, however, the changing energy agenda in Scotland, driven by energy policy and incentives has led to a dynamic where regulation is often responding to national level trends that have scheme and ecological level implications. This is alongside the natural development of the water governance framework in Scotland, as it progresses since implementing the WFD in 2003.

Figure 4.5 presents a timeline of the renewable incentive mechanisms plotted loosely against the some key European regulatory elements, their domestic transposition, and also more responsive issues from water and habitats regulation. It highlights the parallel emergence of renewables incentives, and the wider development and implementation of the current governance framework for water, habitats and species in Scotland. For example, the domestic transposition of the WFD, through the Water Environment and Water Services (Scotland) Act 2003 and resulting 2005 'CAR' regulations, coincides with development under the SRO, and also the RO(S), the main deployment mechanism for renewable capacity in the UK.

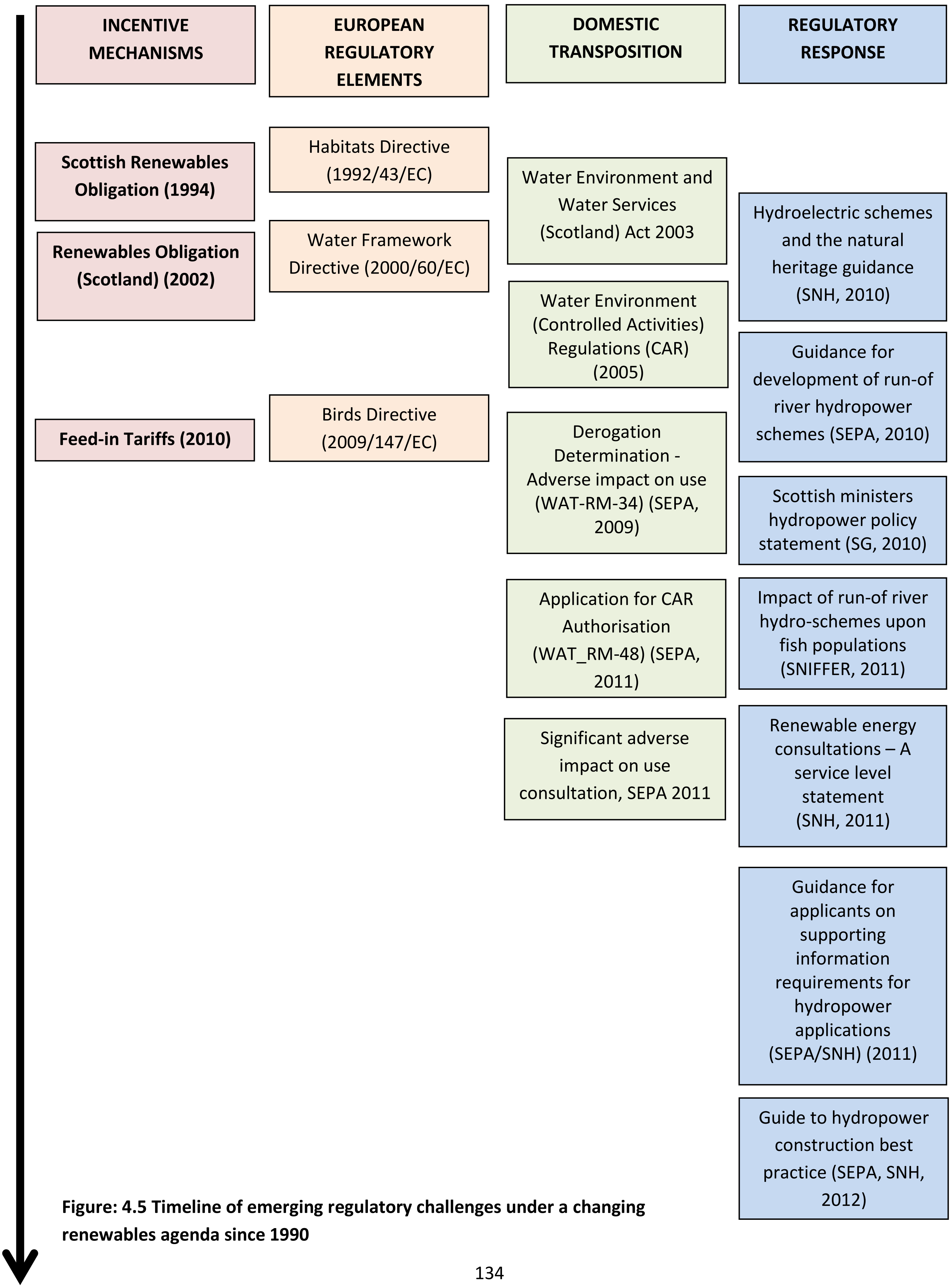


Figure: 4.5 Timeline of emerging regulatory challenges under a changing renewables agenda since 1990

This issue of the *timing* of incentives is interesting, as especially with RO(S) from 2002 and FiTs from 2010, it could be viewed positively as coinciding with a new and progressive regulatory regime that is sufficiently equipped and flexible enough to handle further change through the renewables agenda. Or conversely, it could be seen as more problematic, occurring against a new un-tested regime that is unable to handle additional stresses and uncertainties. Either way, the parallel emergence and continuing development of the two high profile policy areas is a central aspect to hydropower sustainability in Scotland.

Figure 4.5 also shows that there has also been a large regulatory *response* to trends and emerging issues that have stemmed from the changing hydropower and renewables agenda under incentives, especially FiTs. After FiTs were introduced in 2010, SEPA and other regulatory and planning bodies in Scotland were inundated with queries and applications regarding small and community level hydropower generation (ARUP, 2011). Responding to this sudden pressure on their operational capacity, regulators sought to streamline their approach to permitting, and published a small group of associated guidance documents. Guidance was quickly developed by SNH (2010) on hydropower and natural heritage, alongside a SEPA led document on guidance for developers (SEPA, 2010). This initial period of regulatory transition also saw SEPA feed into the development of a hydropower policy statement by Scottish Ministers (Scottish Government, 2010), which clarified that larger schemes making a significant contribution to national targets would be welcomed, as would small <100kW schemes where they could be shown to have no adverse impact on the environment. On the planning side, SNH (2011) issued a service level statement for renewable casework, outlining how they seek to support the development of sustainable hydropower, with a proportionate, risk based approach, but also by feeding into hydropower planning on a strategic level to influence hydropower design and location more widely and at an earlier stage.

Over this continuing period of policy change under FiTs, more specific issues have also been identified and sought to be addressed through the responsive regulation. Given the large uptake in community level micro generation, one example is the uncertainties associated with the impact of high-head run-of river schemes on fish populations (SNIFFER, 2011). Another issue that has arisen under FiTs and the related proliferation of new hydropower developers in the renewables market, is the potential for inadequate construction standards leading to incidents of habitat and species damage through the construction phase of hydropower. At an SNH workshop in August 2012 entitled 'S*haring Good Practice – Hydro-electric development and the natural heritage*' in Perth, Scotland, examples were given of poor construction and restoration practices relating to access tracks for hydropower, and also causing damage to freshwater mussels. In this context, although only fairly recent, the 2005 'Constructed tracks in the Scottish uplands' guidance (SNH, 2005) is set to be updated to reflect the new legislative and policy context, but also the demands and experience of the renewables industry. Specific examples of the influence of the energy agenda, delivered through incentives, resulting in wider trends and regulatory outcomes can also be seen through the case of low-head and storage schemes.

Whereas there is a long history of understanding the potential implications of impoundment hydropower (e.g. Petts, 1985; Petts and Gurnell, 2005; Poff et al., 1997), the ecological effects of low-head run-of river schemes that form part of the large expansion of micro hydropower under FiTs, are poorly understood. Turbine designs such as the Archimedes Screw are often believed to be less damaging to fish than conventional turbines, but this has yet to be demonstrated and it is likely that some species will be more vulnerable than others at different stages of their life history (SNH, 2011). Given the expansion in the number of these schemes, in partnership with other bodies SEPA are developing guidance on low-head schemes to minimise the risk to river ecology.

A similar regulatory pressure exists for specific categories of species, as is the case with rare bryophytes and lichens that inhabit sensitive habitat conditions in western oceanic areas of Scotland. In response to increasing applications for run of river hydropower in this region there is little by way of evidence base to assess the effect of abstraction and moderated flow on spray and the humid riparian conditions needed in wooded gorges and ravines habitats (Demars and Britton, 2011). Sensitivity mapping is now available from SNH to guide hydropower proposals at an earlier stage, utilising a precautionary approach to habitat loss from hydropower.

There has also been a resurgence of interest in pumped-storage hydropower in the last few years due to the valuable flexible generation that can target peak demand, and also integrate increasing amounts of other renewable technologies into the grid (IEA, 2005). Although not solely connected to incentives, but rather to the wider transition to a greater contribution from renewable generation, this trend including the proposed Coire Glas (600MW) scheme has led SEPA to develop new guidance on storage schemes, expected in 2013. Here rather than solely targeting reservoir release, emphasis will also be given to the changing loch level enabling an assessment of changing riparian conditions.

Be it large-scale impoundment schemes in the 1950s and 1960s, or the recent proliferation of micro run-of river generation, the changing characteristics of hydropower presents significant challenges for regulation in Scotland. Often driven through the incentive mechanisms, the changing energy agenda has caused related trends and pressures that require a responsive and adaptive regulatory system.

4.6.4 Potential external synergies

The energy and environmental efficiency of historic schemes presents a further interaction of the incentives and emerging water governance regime under the WFD, but this time leading to positive win-win outcomes. The eligibility criteria of RO(S) allowing for 'renewed' schemes of up to 20MW supports the refurbishment of often large impoundment installations, leading to improved environmental performance and a greater potential for environmental flow management. This eligibility criterion inadvertently provides a specific synergy with the SEPA programme to revise many of the old water use licences for historic hydropower schemes under the WFD, to progressively improve the ecological quality of Scotland's waters. In addition, where SEPA's licence review process does result in a drop in generation capacity at a site or across a generator's fleet, with more flow retained for environmental release as outlined in their 'significant adverse impact on use' consultation (SEPA, 2011b), the RO(S) offers an attractive avenue where generators can recoup hydropower capacity through compensation set schemes on the site of an existing installation.

The case of Fasnakyle Compensation Set at 7.5MW also demonstrates that these additional capacity installations under RO(S), balancing potential generational capacity lost elsewhere, provide little iterative impact and stakeholder objection. In this example it was felt this CS scheme would additionally optimise the size of the statutory compensation flow, which previously was passing through a large 23MW machine running at part load, so would add to the reliability and flexibility and reduce the current environmental risk (Scottish Government, 2004).

Over all, following the dormant phase of hydropower development in Scotland in the 1980s and 1990s, the RO(S) especially has helped to reinvigorate the hydropower sector from a generation perspective as expected, but also provides synergy with elements of sustainability. With the majority of RO(S) hydropower capacity, some 450MW, coming from renewed schemes, its role in raising the efficiency of historic schemes under 20MW is significant. The addition of compensation set generation also provides a vehicle for generation companies to retain some of the generation capacity that may have been lost elsewhere due to improvements in environmental flow. But as shown with Fasnakyle CS scheme, the provision of additional capacity to a site can also raise environmental flow performance of the whole installation and be welcomed by regulatory bodies. Whilst the RO(S) eligibility criteria could be seen to perversely reduce installed capacity in places (SPICe, 2008), the potential for increased output and efficiency leaves the issue not as straight forward (Scottish Government, 2008).

4.6.5 Strategic interaction with regulation

Similar to the NFFO (i.e. Mitchell, 1995), the SRO struggled to deliver on the capacity contracted under the mechanism due to planning and local consents issues. With incentives separate from environmental controls frameworks, this is an early indication of the importance of strategic elements in the energy-regulatory interaction for hydropower outcomes.

The orientation of FiTs towards new, community level generation has led to a proliferation of domestic sized run-of river hydropower schemes in Scotland. With no national coordinating body or plan, or regional and local level integration of spatial issues within the mechanism, however, there is no strategic underpinning to the delivery of hydropower under FiTs. Left unchecked, this leads to a scenario where individual queries and applications are submitted to regulators on a very ad-hoc basis, without an over-arching ‘plan’ or spatial guidance. The result is a series of challenges for the impact and environmental efficiency of micro hydropower in Scotland.

This lack of strategic planning, and the introduction of additional goals for hydropower through incentives, has meant the planning regime has had to adopt a greater strategic role. Helping guide developments towards areas where they can be most easily accommodated within Scottish landscapes, SNH (2011) is part of a wider planning reform that puts greater emphasis on early engagement and development planning. These efforts to try to ensure schemes are located in less sensitive areas works to raise the overall sustainability and environmental efficiency of hydropower in Scotland.

The premise of delivering environmentally efficient hydropower is something that is central to the regulatory approach in Scotland, and relates directly to the wider concept of sustainable renewable energy. Both SEPA (2011) and SNH (2010b) of course state their support for the Scottish Government in delivering on renewable energy targets and commitments. Both, however, also respectively highlight the need to have an 'appropriate balance' between renewable energy and water resource protection, and encourage technologies that can deliver maximum climate change benefits whilst minimising adverse natural heritage impacts.

The central tension through hydropower reflected in this thesis, is between delivering on renewable energy potential capacity and generation, whilst maintaining environmental value and functioning. It is suggested here that the emergence of incentives through energy policy distorts this relationship by adding further elements and complexity to it. For example, rather than targeting installed capacity or generation contribution, the SRO was aimed at lowering the cost of renewable generation by rewarding a small number of competitive low-cost schemes. With the focus of the mechanism on the costs per kWh unit, there is some disparity with the regulatory dynamic discussed that seeks to put value on national level renewable contribution. Similarly, with FiTs the orientation of the mechanism towards domestic and community level generation means there is little contribution to national targets, so there is a shift from schemes being *generation* led, to now being increasingly *income* led, with the difference caused by the incentives that mean generation is not the sole determinant for income. It is only the RO(S) that engages with hydropower in terms of installed capacity, and renewables contribution as a proportion of total national generation, so arguably more easily fits with the common regulatory approach.

With the majority of hydropower regulation orientated towards balancing the renewable energy contribution, and the natural resource implications, the influence of incentives creates a distorting effect by introducing a rewards system that brings in additional goals and considerations for schemes. These additional elements, such as with the guaranteed contracts under the SRO or the specific tariff returns under FiTs, shift simple generation output considerations to additionally include financial aspects. In this context, whereas the bulk of the regulatory focus is often on working with acceptable or justifiable environmental deterioration to enable valuable national renewable energy benefits, there are now considerations given towards other elements also. Outlined above, the energy policy statement by the Scottish Government (2010) sought to address the uncertainty with regards to FiTs schemes stating commitment to them, but reinforcing that no environmental deterioration would be normally permitted for sub 100kW schemes. SNH (2010b) also recognise the renewable energy benefits for rural development and the Scottish economy as a whole.

Given the continuing regulatory approach to balance between renewable energy contribution, and local level environmental conditions, the disconnection between scheme generation and income creates a theoretical strategic problem for hydropower. With the potential for schemes under FiTs to maximise income, rather than generation, due to the incentive framework, the environmental efficiency of a scheme may be affected. At a high level, energy policy often quotes national available resource capacity of a given technology. This is the case for micro-hydropower in Scotland through the work by Forrest and Wallace (2009). To deliver on this resource sustainably, available capacity at viable, environmentally acceptable sites must be delivered, with generation capacity maximised to justify any degradation in environmental conditions. There is anecdotal evidence that down-sizing is occurring by hydro developers under FiTs to maximise revenue, such as by installing a 100kW scheme in a site that could support a 120kW scheme so as to obtain the higher tariff return (ARUP, 2011). Given that the associated environmental implications would not vary much from a 100kW scheme to a 120kW scheme, the loss in generational capacity would seem to be environmentally inefficient. In reality, however, as micro hydropower contributes only a small percentage of hydropower to the national portfolio the national cumulative capacity, and resulting environmental efficiency lost in this way would be small. Nevertheless, it presents an example of how incentives shape the delivery, characteristics and potentially sustainability aspects of hydropower in Scotland.

4.7 RESULT SUMMARY

The governance frameworks and the wider energy conditions for hydropower in Scotland are very different from the NoSHEB era of development in the 1950s and 60s, to the post-privatisation renewables dominated, incentives driven period of the last 25 years. The three main mechanisms examined here, the SRO, RO(S) and FiTs, all vary in terms of their objectives and way in which they support renewables, leading to differing hydropower characteristics and regulatory implications.

This investigation has underlined that whilst they are influential in shaping the characteristics and sustainability implications of hydropower, incentives do not exist in isolation but are one of many influential factors. For example, in reality RO(S) schemes are constrained by site availability and suitability, and regulatory considerations, meaning that a lot of the new stand-alone schemes were run of river, so were neither targeted nor flexible generation stations as might be expected with the market orientated ROCs. Again with FiTs, whilst there is the option to opt out and negotiate export tariffs with suppliers for a potentially higher return, the emphasis on domestic and community schemes, alongside the scale of investment and site availability, means schemes are run-of river and baseload orientated.

With the mechanisms themselves reflecting and delivering upon wider changes in energy policy, they play an important role in shaping regulatory challenges and sustainability outcomes. It has been necessary, however, to unpick the influence of incentives from the above external factors. Nevertheless, from the above comparative analysis of these mechanisms, three key *avenues* for influence have been identified, that contribute to shaping sustainability outcomes for hydropower:

- **Eligibility criteria** – This is obviously fundamental to the type of schemes that are supported, but importantly results in vastly different outcomes. For example, under the SRO, a restricted number of small and economically competitive schemes were constructed, whereas under the RO(S), new build was open to any eligible scheme, in addition to renewed installations. Different again, FiTs brought about a large uptake of micro domestic hydropower schemes due to its orientation and criteria.

- **Financial reward framework –** The way in which the incentives were structured differed dramatically between the mechanisms, resulting in differing objectives and outcomes at a scheme level. The SRO resulted in efficient, low-cost, base-load schemes due to the nature of the competitive entry process, whereas FiTs schemes often targeted domestic tariffs to maximise returns. RO(S) schemes are exposed to market price and variability, but due to external limitations Glendoe is the only high-profile example of where this has led to a storage and peaking scheme, despite their increased value to the grid.

- **Timing –** The objectives and orientation of the mechanisms are shown to be of importance for hydropower outcomes, but the timing of incentives in Scotland themselves are especially important for regulatory implications and challenges. With incentives under the wider renewables agenda emerging in parallel to significant changes and uncertainties with the water regulation framework in Scotland, the way in which the development of incentives fits into and integrates with external governance structures and frameworks is significant.

4.7.1 Identifying six sustainability *outcomes* from incentives in Scotland

From this investigation and through the above three avenues for influence, below are six *outcomes* for hydropower sustainability in Scotland stemming from incentive mechanisms. These outcomes are aspects that have arisen as a result of the energy incentive mechanisms considered, that will influence the overall sustainability of hydropower in Scotland. Therefore, where the incentives themselves have the above avenues or mechanisms in which they can influence sustainability considerations, the following six outcomes are the resulting outcomes, challenges or synergies that occur as a consequence.

1. Parallel emergence with water regulation –The timing and growth of schemes under the RO(S) and FiTs coincided with a new and evolving system of water regulation. This coincidence can be viewed as problematic, stressing an untested regulatory system that must reconcile the large number of new applications whilst meeting the stringent objectives of the WFD. Or alternatively, the timing could be seen positively, with the new and changing regulatory regime being flexible and responsive enough to respond to the changing energy agenda.

2 Strategic challenges – It has already been established that construction rates under the SRO and the NFFO were lower than expected due to environmental regulation and local connection issues. The lack of integration with the regulatory system, and with no overseeing body or strategic spatial plan, also presents a strategic challenge for regulation under FiTs. With no coordination to site development, there is pressure on the planning and permitting system as a result of the inundation of queries and applications, and forcing the need to develop strategic capacity to guide development towards low-risk areas.

3. Synergy with water regulation – With RO(S) eligibility extending to existing schemes (<20MW) built or refurbished since 1990, the mechanism has acted as a catalyst for generators to revisit and refurbish many existing historic sites. Improving schemes’ efficiency, environmental flexibility and performance, this aspect provides a direct synergy with a SEPA programme to revise water use licenses under the WFD. Additionally, where these regulatory measures divert more flow for environmental release, resulting in less capacity available for generation, the RO(S) offers an attractive avenue where generators can recoup capacity by adding compensation set capacity on existing infrastructure. These CS additions have also been seen to result in little stakeholder objection, and can offer a more flexible release profile.

4. Disrupting environmental efficiency – With hydropower regulation traditionally orientated to reconcile and balance the renewable energy benefits with water resource implications, FiTs has created a theoretical disconnect between generation and income, disrupting the environmental efficiency of schemes. The FiTs framework introduces an incentives system that means schemes target income, rather than simply generation, meaning the environmental efficiency of a scheme could be reduced and potential site capacity not realised.

5. Responsive regulation – The changing energy agenda, conveyed through these incentives created a scenario where regulation has had to be very responsive and flexible, addressing a number of trends and pressures on the natural environment. Emerging issues such as construction standards and access tracks, alongside uncertainties regarding bryophytes, low-head schemes and pearl mussels for example, has required regulation to be responsive and adaptive, but at the same time retaining robustness in its decision making and evidence base.

6. Scheme type and characteristics - A final outcome from incentives that feeds into hydropower implications and issues of sustainability is, of course, the way in which it feeds into determination of scheme type and characteristics. With SRO schemes having fixed price contracts and tight competitive finance due to the entry criteria, this was more suited to run-of river schemes. Whereas under the RO(S) eligibility extended to renewed existing and historic schemes, and encouraged new larger stand-alone hydropower, as well as additions to existing sites. Finally, the FiTs mechanism specifically targeted community and domestic generation, with the micro generation run-of river schemes often pitched under the 15kW tariff threshold to take advantage of its higher relative return.

An additional area for research would be to use these sustainability outcomes to inform consideration of sustainability monitoring and reporting (e.g. SDC, 2011). For example, where the RO(S) has offered synergies with the WFD and led to improvements in stretches of water bodies' ecological status, this could be quantified on a regional and national level. With the RO(S) leading to a specific number of scheme refurbishments (SPICe, 2008), this presents a specific opportunity to measure the resulting benefits for river ecology and hydropower sustainability.

4.8 THE FUTURE FOR RENEWABLE INCENTIVES IN SCOTLAND

The last 25 years have seen the emergence and development of renewable energy incentives in Scotland, which have shaped the resulting characteristics and sustainability of hydropower. The evolving basis and emphasis of these incentives and wider energy policy, in addition to the changing wider context for hydropower, indicates that future outcomes may be different again.

Around 20% of the UK's total electricity generation capacity from 2011 is set to close by 2020, with an increasing reliance on potentially intermittent wind, and inflexible nuclear. In response to this trend and the wider transition to low-carbon generation, the UK government is undertaking the Electricity Market Reform (EMR), to deliver the frameworks and investment needed to meet climate, security and affordability challenges (DECC, 2012f). A key new mechanism arising out of the EMR is the Feed-in Tariffs with Contracts for Difference (CfD), set up to provide long term contracts for low carbon generation.

CfD is going to be the main renewables support mechanism in the UK, running in parallel to the RO and RO(S) from 2014 and replacing it from 2017. RO schemes accredited up to 2017 will still obtain the 20 year support up till 2037. Under the CfD mechanism generators with a sell their electricity as normal to the market wholesale price, then depending on if this is above or below an estimated long term electricity 'strike' price, needed to bring forward investment in a given technology, the CfD pays the difference. This means if the market price is above the strike price, the generator pays the difference back, but if it is below the strike price then the generator receives a top-up payment.

CfD therefore seeks to stabilise returns for generators, and removes exposure to long term price volatility and accompanying commercial risk, therefore encouraging investment and the raising of finance. The mechanism is open to low-carbon technologies that are not eligible for FiTs, meaning hydropower and renewables over 5MW, and also nuclear and schemes with carbon capture and storage (CCS) are included. The strike price is set administratively for renewables for each technology, with future strike prices fixed when in a contract, but decreasing year on year for new entrants, reflecting cost savings and growth in the supply chain. The strike price for renewables may vary by country within the UK (DECC, 2012g).

4.8.1 Examining the potential influence of the CfD

The body of this research was conducted when detail on the structure and weighing of the CfD mechanism still to be decided. Although more information has now been released whilst corrections are being made to this thesis, without a new full assessment it is difficult at this early stage to identify specifically what CfD will mean for hydropower in Scotland. However, in the above analysis, three avenues were identified in which the characteristics of incentives mechanisms can shape the outcomes for hydropower, namely eligibility criteria, financial reward framework and timing. Where possible these can be applied to CfD to help understand the potential influence for hydropower in Scotland.

The **eligibility criteria** for CfD extends to new schemes not supported under the RO(S) or eligible for FiTs, so must be above 5MW. With significant site and regulatory limitations on new large hydropower schemes in Scotland, it is unlikely there will be a sudden large uptake in hydropower deployment under the mechanism. This is additionally the case as unlike under the RO(S) it does not formally allow for renewed existing schemes.

Continuing from the RO(S) and its favourable weighting for marine and offshore technologies reviewed in 2012 (Scottish Government, 2011a), the CfD is also primarily orientated towards establishing these emerging technologies, due to their large potential contribution but lower market competiveness. The level of support under the CfD for hydropower is set to be in line with the current Scottish RO(S) level (1 ROC/MWh) rather than the recent level of 0.7 ROCs for England and Wales, as most of potential further sites are in Scotland (DECC, 2013). This perhaps leaves hydropower in Scotland in a similar position as it is currently under the RO(S). DECC (2013) have hinted that with a number of large hydropower schemes coming to the end of their lifecycles, support under the CfD for repowering and replacement of large existing plants may be available, on a case by case basis. Similarly, larger hydropower (>50MW) will have their contract length and support level decided on a case by case basis (DECC, 2013). Nevertheless, hydropower above the 5MW threshold is well developed in Scotland, with potential additional sites also well researched and understood by generators. It will be down to the underlying economics and weighting of the mechanism, and strike price for hydropower, which is comparable as to both that under the RO and relative to other technologies under the CfD, as to whether these potential sites will now become viable and developed.

Whilst there is a requirement for applicants to simply identify which environmental licences are needed for generation under the CfD; there is no integration between the mechanism and environmental regulation. Allocation rounds will be run every six months, to allow a managed deployment at the right level and price, allowing a form of strategic control, but this is more on the basis of ensuring value for money and that the mechanism is pitched correctly, rather than regulatory and local environmental efficiency.

It is certainly clear that as a CfD, the **financial reward framework** is structured to provide greater financial certainty and stability for generators than the RO(S). Depending on how often the price for electricity is balanced, for instance over a monthly, weekly or daily period, protecting the generator from market price volatility, it therefore suits less flexible, base-load schemes. Again given the site availability and regulatory constraints, this scenario would seem to support small to medium sized (>5MW) run-of river schemes, which is confirmed by DECC (2013).

It is the intention of DECC (2012g) that once established, a later iteration of CfD will reflect the difference between intermittent and baseload generation, and encourage them to operate at a higher-continuous load. Furthermore, and importantly for future peaking and storage hydropower in Scotland, DECC are exploring how they can develop an additional CfD with a structure that brings specific investment tailored to flexible (low-carbon) generation, to vary output with demand, offsetting intermittent renewable generation. Given the increasing value on pumped-storage for its grid balancing capabilities (National Grid, 2012), displayed through changes to the operation of Cruachan, or the proposal for the 600MW Coire Glass scheme what would only be the third of its kind in Scotland, future iterations of the CfD could work to make future pumped-storage schemes, although very expensive and site dependant, increasingly viable.

Given the experience with RO(S) and FiTs, the **timing** of the CfD is also of interest for hydropower in Scotland. Building on an enviable natural resource base, the Scottish Government has shown strong climate leadership through the far reaching Climate Change (Scotland) Act 2009, with action on Energy Policy for Europe mandating 20% of all energy to be renewably sourced by 2020, and a stringent domestic aspiration to generate 100% of electricity used from renewables by the same date.

A similar programme is now underway to orientate Scotland as a ‘Hydro Nation’, to realise, protect and deliver on the high value of the water environment and sector, in a changing and often stressed hydrological world. It outlines leadership and strategic thinking are needed to deliver on a low-carbon water industry, and support a low-carbon wider society for the next ten to twenty years (Scottish Government, 2012b). This trend towards a greater economic and societal appreciation of the value of the water resource is increasingly the context for hydropower in Scotland, so will be of relevance to development under CfD. Although the Hydro Nation looks to identify and secure the heritage value of Scotland’s water environment, its service value is also considered, which may extend to sustainable, high-value schemes that make a significant contribution to national needs.

The CfD will also coincide with the second cycle of river basin management planning (RBMP) (2015-2021) aimed to make incremental improvements against WFD targets. Although more related to integrated catchment management, targeting physical change and pollution from agriculture and land use activities, this reflects the development and maturation of the water governance and regulatory system under the WFD in Scotland. As such, the licensing and consents frameworks for hydropower will be much more established and experienced, and industry will be more accustomed to working with it and its requirements. It is felt this will provide a degree of stability and consistency, ultimately supporting a smoother relationship with decreased uncertainties and tensions.

4.9 DISCUSSION

This research set out to evaluate critically the role of incentive mechanisms in shaping scheme and sustainability outcomes for hydropower in Scotland. Given the interaction of energy and water policy at all scales (Volkery et al., 2011), an increased understanding of the way in which incentives frameworks shape hydropower and regulatory outcomes is of key importance to issues of sustainable water resource management, and policy coherence and synergy. Fostering communication and exploring linkages between disciplines and scales ultimately serves to inform debate and decision making to deliver increasingly sustainable renewable energy, in a changing world.

This research has shown that as part of the wider renewables agenda, incentives play a significant role in shaping hydropower outcomes in Scotland, leading to both negative trade-offs, and positive synergies for the sustainability of hydropower. This work innovatively identifies not only the sustainability *outcomes* themselves, presenting them as 6 key aspects, but also the ways in which these are caused by incentives, applying these three 'avenues for influence' to the upcoming CfD mechanism. This explicitly engages with the ways in which disciplines interact, and how top level policies can feed into shaping scheme and ecological level outcomes.

Previous academic work has critically reviewed the effectiveness of incentives for delivering renewable capacity (e.g. Mitchell, 1995; Connor, 2003; Mitchell and Connor, 2004), and looked into the effectiveness of their support for hydropower (i.e. Harrison, 2005). This research therefore fills a niche that contributes to informing the challenge of sustainable renewable energy in a changing world, by highlighting the avenues and outcomes from the three main incentive mechanisms that have delivered the renewables agenda over the last 25 years.

The outcomes from this research can feed into both the regulatory side, by informing its response and future licencing approach and frameworks, and also the energy policy disciplines, as we soon transition from the RO(S) to CfD as the main mechanism to deliver renewable energy. Notably this research shows that whilst there are some tensions and trade-offs driven by the renewables agenda and through specific aspects of the incentives considered here, crucially there is the potential for synergies between these policy areas through energy incentives.

The energy sector in Scotland, the rest of the UK and Europe faces significant challenges in delivering an affordable, secure and low-carbon system, both now and into the future. With an established renewables capacity, and significant additional resource potential, Scotland is at a crucial point where it now must develop further capacity, but ensure protection of its valuable natural heritage. Ultimately, as additional capacity is developed, this tension will be much more acute as less ideal sites are pursued.

After 25 years of emerging and evolving renewable incentive mechanisms in the UK, this thesis makes the argument that advent of CfD presents a significant opportunity to now integrate sustainability and environmental monitoring and reporting from the outset (e.g. SDC, 2011). These mechanisms are commonly reported in terms of MW installed capacity, but reference to emissions avoided in terms of carbon or GHGs indices could be a simple additional step in terms of sustainability monitoring. For hydropower, with quantifiable carbon savings but also the potential for downstream hydrological impacts, or even benefits, as was seen with refurbished schemes under the RO(S), a matrix, perhaps with a final reported rating, reflecting the energy benefits and potential water environmental trade-offs of a scheme would be an innovative and useful way to track the sustainability implications of the mechanism into the future.

A fair degree of uncertainty remains for the future of hydropower under incentives, namely the upcoming CfD mechanism, which will become clearer as further details are announced. Nevertheless, this research has highlighted the avenues by which incentive mechanisms help shape outcomes for hydropower sustainability, so it will be of use as more information becomes available.

CHAPTER FIVE: A COMPARITIVE ASSESSMENT OF SCOTLAND AND NORWAY TO INFORM UNDERSTANDING OF HOW FRAMEWORKS AND CONTEXT FOR HYDROPOWER INTERACTS WITH AND INFLUENCES ITS SUSTAINABILITY AND OUTCOMES

5.1 INTRODUCTION

The historical emergence of hydropower in Scotland, and continuing changes in its wider context, have shaped its characteristics and in turn framed the resulting challenges for sustainability. By identifying the linkages and creating dialogue between disciplines and scales, this thesis seeks to inform the pursuit of sustainable renewable energy through policy and regulation. This is of increasing value as the UK continues on a path of increased renewable energy uptake, but also must deliver on environmental and resource protection goals.

This chapter further examines and reflects upon on hydropower trajectory in Scotland using the experience in Norway as a comparative example. It provides a novel and timely mechanism to further understanding of how wider contextual conditions, such as energy policy, and their change, can shape the characteristics, challenges, approaches and outcomes for hydropower.

5.2 THE CASE FOR COMPARISON

With a temperate maritime climate and high annual rainfall (Johnson, 1994), alongside modest evaporative demands (Marsh and Anderson, 2002) and a diverse yet often steep topography resulting in high runoff per unit area (Gilvear et al., 2002), Scotland has an enviable hydrological resource base. As a result it has a long history of water resource use, and is the principal generator of hydropower in the UK, contributing over 90% of 2010 production (DECC, 2012).

Although globally Scotland's hydropower production (3.3TWh) and installed capacity (1.4GW) is relatively small (Scottish Government, 2012), as a percentage of total domestic electricity generation (2010) it is in the top ten countries worldwide (IEA, 2011). Of these hydropower producing nations, Norwegian output (118TWh) and capacity (30GW) (2010) dwarfs that of Scotland, but nevertheless provides an interesting basis for comparison, to examine how the overall frameworks and context for hydropower interacts with and influences its sustainability and outcomes in the two countries.

Located at the north-western part of the Scandinavian Peninsula, Norway is in relatively close proximity to Scotland, which increasingly displays a north Atlantic hydroclimate, diverging from that of the southern UK (Roald, 1998). Present hydropower capacity in Norway is also supported by a large expansion in the mid-20th century, similar to that of Scotland (Payne, 1988), with the technology again playing a key role in economic growth and welfare, and supporting the wider industrialisation of the country (Angell and Brekke, 2011).

More recently through its hydropower resource, Norway has also orientated itself as a renewables leader in Europe, showing a similar political and regulatory commitment to sustainable renewable energy (Knudsen and Ruud, 2011) to that of Scotland (Scottish Government, 2010). Given the sustainability challenges hydropower faces through reconciling often competing energy and environmental policy goals, both countries are notably subject to the EU's Renewable Energy Directive (2009/28/EC), and the Water Framework Directive (WFD) (2000/60/EC), with Norway qualifying due to its status in the European Economic Area (EEA).

In pursuit of the central aim of this thesis, which seeks to develop understanding of the influence a changing wider energy context has on the characteristics and sustainability of hydropower in Scotland, this present chapter provides a comparative analysis of four high profile regulatory challenges present in both Scotland and Norway, covering:

- Historical trajectory and current characteristics

- Existing licence reviews under the WFD

- Mitigation development and application

- Small and micro hydropower regulation

These elements were chosen due to their importance for sustainability considerations, and their current relevance to regulatory bodies. For example, licence reviews under the WFD and the licensing of small and micro hydropower are two high profile issues, which continue to dominate sectoral activity in Scotland (Scottish Government, 2011) and Norway (Knudsen and Ruud, 2011), and provide examples of where a strong renewables agenda can shape water regulatory challenges and environmental decision making.

This comparative assessment will be of interest to hydropower stakeholders in both countries, but also those involved with wider policy and regulatory design and harmonisation, in environment and energy domains. This work fills, in particular, a significant gap in knowledge regarding how environmental challenges and decision making, often at a local scale, is influenced by the changing wider context and development of renewables at national and European levels. Whilst this comparative chapter seeks to avoid duplication of information from elsewhere in this thesis (such as the technical discussion presented in Chapter 4), some reappraisal of information is necessary to support the comparative analysis between hydropower in the two countries.

5.3 AN OVERVIEW OF HYDROPOWER PORTFOLIOS

5.3.1 Scotland

Aside from some small-scale developments such as those on the Clyde in Lanarkshire, the initial development of hydropower in Scotland was primarily to support the aluminium smelting industry in the 1920s. The high energy needs of the British Aluminium Company were met by private schemes at Kinlochleven (24MW) and Lochaber (64MW), with large storage reservoirs, hydrological alteration and a high load factor, base-load generation (Payne, 1988). These schemes often had little environmental flow mitigation (Reid, 2002).

A significant proportion of the 1.4GW of current hydropower capacity (excluding pumped storage) in Scotland, however, is provided by large historic schemes constructed later in the 1950s and 60s under the North of Scotland Hydro-electricity Board (NoSHEB), formed in 1943 to develop hydropower projects in the Scottish Highlands. This era marks a phase of development in hydropower environmental governance (Reid et al., 2004; 2005), in turn shaping scheme characteristics, and concessions to environmental considerations.

5.3.1.1 Hydro Board and pumped storage

Taking Department for Energy and Climate Change (DECC) data for existing power stations in the UK above 1MW capacity (DECC, 2012d), sorted for Scottish hydropower, and adding and cross-referencing those schemes that currently operate with Renewable Obligation Certificates (ROCs) (Ofgem, 2013), **Figure 5.0** offers an overview of hydropower in Scotland. It highlights the historical emergence and changing characteristics of schemes, alongside the significant contribution that NoSHEB schemes make to the current hydropower portfolio. Micro-hydropower (<100kW) and FiTs level schemes are less well reported in this way, so are omitted.

The NoSHEB period of development contributed 28 conventional hydropower schemes, comprising 66 dams, 51 power stations, 171 miles of tunnel and 103 miles of aqueducts (Payne, 1988).

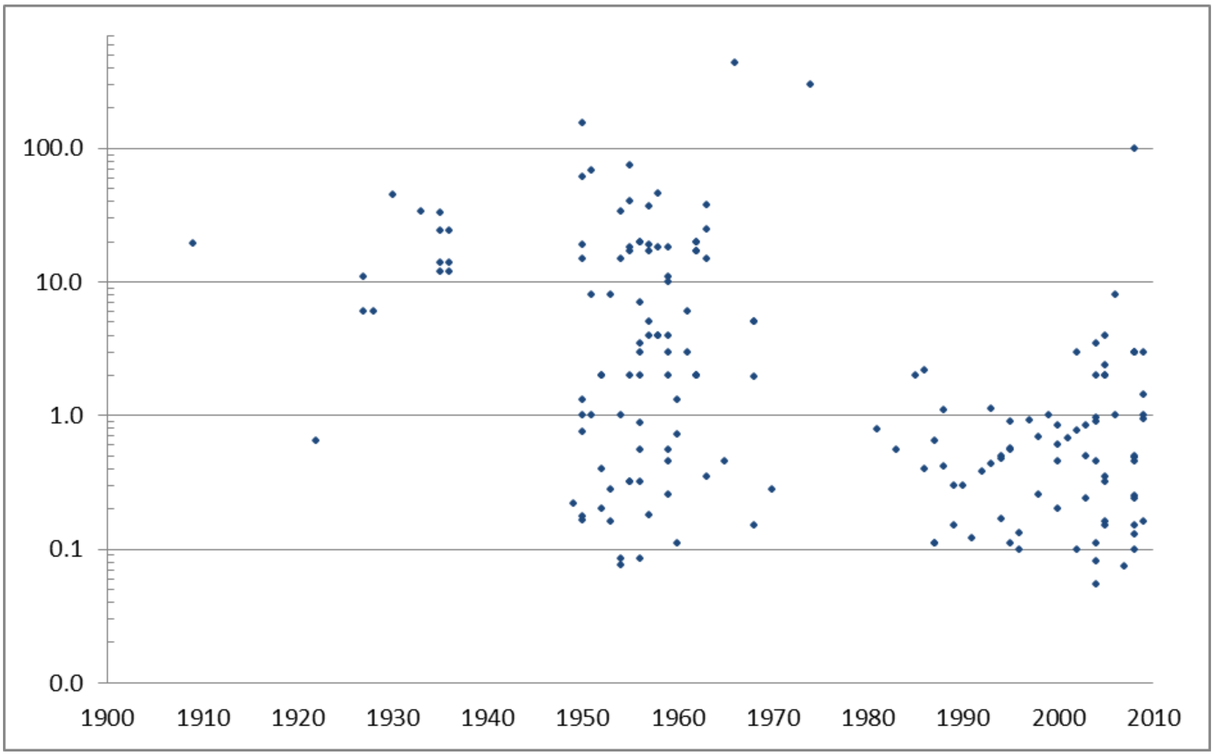


Figure 5.0: Historical hydropower development in Scotland, scheme capacity (MW) and year of construction (excluding micro schemes)

A distinct characteristic of these early schemes was often the creation of large storage reservoirs, with a system of complex abstractions, often diverting the maximum quantity of water from surrounding catchments through a series of turbines to ensure economic viability and to accommodate seasonal precipitation variations at a site. One example is the 100MW Conon development, constructed over three phases, which in its completed form has eight dams, nine tunnels and six power stations, transferring surface water from several river catchments and resulting in an often highly modified hydrological regime (SNH, 2002).

A shift occurred in the mid-1960s, by when many of the most economically attractive sites for storage schemes had been developed, and the focus moved to pumped storage schemes as an alternative, to balance the output of large thermal and nuclear stations being constructed at the time. In this period the Cruachan (440MW, 1966) and Foyers (300MW, 1974) pumped storage schemes were constructed. These two schemes were aimed primarily at energy transfer, utilising the output of conventional thermal and nuclear stations that provide the backbone of electricity generation in the UK (Johnson, 1994).

The increasing scale and technical efficiency of thermal and nuclear stations, the discovery of North Sea oil (Payne, 1988), and the growth in environmental awareness and regulation (Reid et al., 2004), all led to a period of inactivity in the construction of new larger hydropower schemes in Scotland from the 1970s to the mid-1980s, as reflected in **Figure 5.0**.

5.3.1.2 Smaller schemes and the renewables agenda

Although there were a few new schemes in the 1980s, it was not until the 1990s and under the renewables agenda that further hydropower development occurred in Scotland. A series of evolving renewable incentive mechanisms continue to shape the wider renewables sector, and hydropower of all scales in Scotland.

The Scottish Renewables Obligation (1994), Renewables Obligation (Scotland) (2002), and Feed in Tariffs (2010), all support renewable development, but have slightly different objectives, incentive frameworks and emphasis, resulting in distinct outcomes for hydropower in Scotland. An in depth examination of how incentives have shaped the characteristics and sustainability outcomes of hydropower in Scotland has been provided in Chapter 4 of this thesis.

In contrast to the characteristics of the historical development, apart from the exception of Glendoe, new hydropower in Scotland is more likely to be smaller run-of river schemes, with additional large storage schemes unlikely due to environmental considerations and site availability (AEA, 2010; DECC, 2011b; Scottish Government, 2011).

5.3.1.3 Identifying categories of hydro schemes in Scotland

The pattern of historical emergence and continuing development of the Scottish hydropower sector has provided a changing context for new schemes, driving their characteristics and in turn shaping the subsequent implications for sustainable water resource management. Given this formative development profile, it is possible to characterise the hydropower portfolio in Scotland by identifying broad categories of schemes with shared characteristics. Through consideration of the changing prevalence of these categories over time it is also possible to evaluate the changing regulatory implications of hydropower in Scotland, and to project those implications and their likely consequences into the future.

A variety in scheme type manifests through differences in the design, size, location and operational characteristics of hydropower (Petts, 1984). The differing scheme objectives, and way in which river flow is utilised, leads to corresponding implications and outcomes for water ecology and water resource management (Richter and Thomas, 2007). Reflecting the way in which hydropower schemes harness and potentially disrupt the natural flow regime is therefore an appropriate and justifiable basis on which to characterise and categorise the variety of schemes in Scotland. These categories also influence other regulatory challenges, through shaping landscape, habitat and ecological pressures.

The following subsections outline the scheme categories that have been identified, with a brief justification of their inclusion.

i) Pumped storage schemes

Pumped storage schemes are distinct from conventional storage and run of river hydropower schemes in the way that they seek to re-use all or a proportion of a stored water body. Their large capacity, and distinct operational approach means they present a particular set of water management challenges. Although there are only two pumped storage schemes in Scotland (Cruachan, 440MW, 1966; and Foyers, 300MW, 1974), their role in balancing the grid, complementing the output of large thermal and nuclear stations is still very relevant. As seen by the 2012 application by Scottish and Southern Energy (SSE) for the Coire Glas (600MW) pumped storage scheme, however, it is still also an attractive option in the context of growing the proportion of intermittent renewable generation (Scottish Government, 2010b).

ii) Hydro Board large impoundment and in-river schemes

As discussed, the period 1950 to 1965 marked a key episode in hydropower development in Scotland, resulting in significant capacity that continues to provide a valuable contribution to the current renewables portfolio. Whilst the sheer number of schemes and associated infrastructure means great variety between installations from this period, the impoundment characteristics and large scale hydrological alteration that the schemes present are distinct from current approaches, and so present their own continuing set of water management tensions. Impoundment schemes of this type can be baseload or peaking in their generation orientation, and some create or utilise a reservoir, whilst others are more in-river by design. Some of these schemes have also been 'renewed' under the RO(S), such as the in-river Kilmorack (20MW) and Aigas (20MW) sites.

iii) Contemporary impoundment schemes

Following the period of expansion under the Hydro Board, we have seen a trend for contemporary schemes to be much smaller scale, and rather than rely on impoundment and a storage reservoir, utilise a run-of river approach. There is, however, a small number of exceptions to this trend, including the 100MW Glendoe impoundment scheme (2008), and separately the 4MW Kingairloch (2009), which utilises the existing Loch Uisge. Whilst these two schemes are quite dissimilar, they are two recent cases that represent a slightly different approach to contemporary hydro schemes.

iv) Larger run of river schemes

Following the introduction of the SRO and RO(S) mechanisms, a significant number of larger run of river schemes operate between 100kW and 5MW. Whilst representing a fairly large variety in capacity, these commercially orientated run of river schemes will share a common approach in the way they utilise river flow for generation. The 2MW Garrogie scheme to the east of Loch Ness for example is a typical run of river scheme, constructed under the SRO that abstracts a proportion of the flow of the River Fechlin, through a 2.5km penstock, creating a 2.75km depleted reach. The RO(S) has resulted in the development of additional run-of river capacity on existing, often historic impoundment schemes, in the form of compensation set run of river hydropower, such as at Fasnakyle (8MW, 2006).

v) Sub 100kw run of river schemes

The advent of the 2010 FiTs mechanism opened up the hydropower sector in Scotland to much smaller, domestic and community scale schemes, with tariffs up to 5MW. The sub 100kw range however represents a vibrant area of growth in Scotland due to the tariff thresholds at ≤15 kW (21 p/kWh) and >15 - 100kW (19.7 p/kWh) capacity which are of relevance to domestic and community generation. Scottish Ministers outlined (Scottish Government, 2010) that whilst sub 100kW schemes provided local socio-economic benefits, their reduced contribution to the national renewable portfolio meant that a stricter regulatory approach would be taken with them. This precedent, and subsequent SEPA guidance for run of river schemes (SEPA, 2010), makes it explicit that the consideration and regulation of this scale of scheme is an important aspect for future sustainable renewable energy in Scotland. Low-head, ‘Archimedes’ type schemes are also included in this category.

Applying the available scheme data to the above categories and characteristics, **Table 5.0** provides a breakdown of the number and capacities of hydropower schemes in Scotland against this framework. Describing the characteristics of hydropower in Scotland, it is once again reflective of the historical development but also the changing generation objectives, and site and regulatory constraints.

Category	Frequency	Total Capacity (MW)
i	2	740.0
ii	48	1,165.5
iii	2	103.5
iv	230	157.2
v	241	3.0
Total (non-P/S)	**521**	**1,429.2**
Total	523	2,169.2

Table 5.0: The number and capacity of hydropower installations against the above categories (DECC, 2012d; Ofgem, 2013) (Highlighting totals with and without pumped-storage)

For example, whereas the majority of capacity comes from category ii (Hydro Board impoundment schemes), the current development of further impoundment schemes (category iii) has been limited. In addition, following the recent large uptake in sub-100kW run of river schemes, they are now of a similar magnitude to the larger run-of river schemes that have existed previously, but due to the scale at which the development is orientated, sub-100kW schemes account for little in terms of national contribution. Future hydropower development in Scotland is expected to take the form of category v, and to a lesser extent category iv, perhaps including compensation set capacity added to existing schemes. It follows, therefore, that future challenges for hydropower regulation and sustainability in Scotland will be tied to the characteristics of (iv and v) larger run of river schemes and sub 100kW schemes, which will be explored later in this chapter.

5.3.2 Norway

Similar to the experience in Scotland, the emergence of hydropower in Norway displays a historical profile, with distinct phases of development reflecting changing circumstances and context.

5.3.2.1 Early emergence of hydropower in Norway

Following full independence from Sweden in 1905, a significant period of industrialisation in Norway followed, supported by pioneering hydropower development. The emerging electrochemical and fertilizer production industry, including new techniques developed by the part publicly owned Norsk Hydro, required large amounts of electricity, so helped to catalyse the first significant phase for hydropower development from 1907 to 1916 (Brekke, 1996). In this period, against the backdrop of the growing industrialisation of the country and rising electricity demand from industry, the Norwegian state purchased the rights to many waterfalls in Norway for hydropower development (Statkraft, 2009).

Waterfalls at Rjukanfossen and at Svelgfossen were developed for hydropower by Norsk Hydro following state acquisition. The latter, which is located on the Tinnelv River just north of Notodden in Telemark, was a significant development. Whilst also regulating the outflow of Tinnsjø and Møsvatn lakes, at 92MW it was the second largest scheme in the world when constructed in 1907. The total installed capacity in Norway by 1908 was 200MW (Brekke, 1996).

In 1917, the Industry licencing Act, and the Watercourse Regulation Act were both established, setting the framework for hydropower governance, and enshrining principles of public ownership and ensuring local and regional remuneration. The Norwegian Water Resources and Energy Directorate (NVE) was also established in 1921, with responsibility for the construction and operation of state owned hydropower. Significantly, providing a large degree of sectoral continuity, these are all elements of governance that still remain for hydropower in Norway.

5.3.2.2 Significant growth and the current agenda

A second development phase followed from 1945, with a number of large capacity schemes including the 430MW Tokke scheme in Telemark (1961), and 300MW Nedre (‘lower’) Røssåga (1958) supplying ironworks in Nordland (Statkraft, 2009). The Lower and 'Upper' Røssåga schemes created a large reservoir, flooding swamp and forested areas, with lake Stormyrbassenget in Hemnes, Nordland county, serving as an intake reservoir upstream. The Stormyrbassenget has since been subject to management changes, with the two Røssåga installations coordinating and adapting operations to stabilise reservoir level to serve the interests of nesting birds and wetland ecology (Statkraft, 2013).

In terms of capacity, the most significant period of development in Norway was 1970-1986, where an additional 10730MW installed capacity was added (Anderson, 2006). This includes the 1240MW pumped storage scheme at Kvilldal (1986), the 1120MW conventional scheme at Sima (1980), and the 960MW peaking scheme at Tonstad (1968). **Table 5.1** presents the ten largest hydro stations in Norway, by construction year, and shows that the five largest capacity schemes were constructed in this important period. Notably, these ten largest schemes average 25% of current annual electricity generation in Norway (NVE, 2011).

Power Station	County	Capacity (MW)	Year
Kvilldal (P/S)	Rogaland	1240	1986
Sima	Hordaland	1120	1980
Tonstad	Vest-Agder	960	1968
Aurland 1	Sogn og Fjordane	675	1973
Saurdal (P/S)	Rogaland	640	1985
Rana	Nordland	500	1967
Tokke	Telemark	430	1961
Holen (P/S)	Aust-Agder	390	-
Tyin	Sogn og Fjordane	374	1942
Svartisen	Nordland	*350	1993

Table 5.1: Ten largest capacity hydropower stations in Norway (NVE, 2011) (*Original capacity)

After 1990, with such schemes becoming controversial and ideal sites having been developed (MoPE, 2008), Ministers signalled in 2001 that the development of further large capacity schemes, with large reservoirs and hydrological alterations, is now unlikely in Norway. This policy statement has left three remaining development paths (Knudsend and Ruud, 2011):

- Construction of small scale hydropower (<10MW)
- Refurbishment and upgrade of existing hydropower
- Reviewing operational licenses

Small hydro in Norway is categorised as being under 10MW capacity, which still allows for a fair amount of diversity in scheme types and generational approaches. With this shift in development, future new schemes are likely to be similar in size and approach to the 9.2M Uleberg scheme in Aust-Agder. Utilising a 180m head on the river Skjerka, the 2007 scheme has two Francis turbines and took 16 months to construct (Anderson, 2006).

With this transition, however, there have been associated regulatory outcomes. Around 2006 for example, the Norwegian hydropower regulator (NVE) received in the region of 250 applications for such schemes, putting pressure on its operational capacity and ability to approve schemes in a timely manner (Anderson, 2006). The development of hydropower in Norway has also seen it expand internationally through the export of Norwegian technology and industry, with Statkraft hydropower developed in Sweden in 2005, then from 2009 in Germany, Wales and Turkey (Statkraft, 2009).

5.3.2.3 Characterising current hydropower

The Norwegian hydropower sector is reliant on large reservoir storage schemes to balance the large precipitation input from spring upland snow melt with increased winter energy demand, and protect against potential annual variability in both. Accounting for 80% of hydropower production, reservoir schemes in Norway therefore have an important strategic role and are central to national security of supply (MoE, 2012).

A typical large Norwegian hydropower development, such as that on the Orkla River system, consists of multiple large natural or artificial impounded reservoirs located high up in mountainous areas. The impoundment reservoirs are fed by catchment abstraction and seasonal snow melt, often serving an initial series of generation stations, then a further tier of reservoirs or a river system with a series of in-river type plants in lower altitude river systems. This approach seeks to optimise the use of water, raising the amount generated per unit, thus making the generation-impact ratio more environmentally efficient (Statkraft, 2009).

The wide variability in water course type and local hydrological conditions contribute to shaping hydropower characteristics in Norway. A west-east distinction exists where variations in topography, precipitation and climate mean that in western Norway, such as in Nordland and sections of Troms counties, rivers are generally short and steep with large waterfalls. In eastern Norway, the Trøndelag region and Finnmark county, have longer river systems, with a lower gradient, but larger volume (MoPE, 2008). Due to these conditions, Norway's large capacity, high-head schemes, often with large storage reservoirs and inter-basin transfer are commonly found in western Norway. One example is the 1240MW pumped storage scheme at Kvilldal, part of the massive and considerably wider 2100MW Ulla-Førre development. By contrast, Norway's in-river hydropower schemes are commonly situated in eastern lowland areas and Trøndelag, such as along the 372-mile long Glomma river, which has a drainage basin covering 13% of the country. The Solbergfoss power station on the Glomma river at Askim in Akershus county, has a capacity of 208MW, including one Kaplan turbine of 100MW (MoPE, 2008).

5.3.3 Outcomes for Scotland and Norway

Below is a simple comparison of the distribution of the number of schemes (**Figure 5.1**) and the total capacity of schemes (**Figure 5.2**) against five capacity groupings, for Scotland and Norway. These figures allow the characteristics of hydropower in the two countries to be compared easily. Although there is a greater overall number of schemes in Norway, **Figure 5.1** shows that there are similar numbers of micro and small hydropower schemes in the two countries. Thus, when considered as a proportion of total national scheme numbers, Scotland has a higher proportion of <100kW schemes (46%) and 100kW to 1MW schemes (37%) than Norway (14% and 17% respectively). Consequently, the opposite is true for schemes over 1MW in Norway, which represents the majority of schemes in the country. Given the greater number of total schemes, and the greater proportion of larger capacity schemes in Norway, **Figure 5.2** shows the much higher contribution in capacity from schemes over 1MW in Norway. This pattern is certainly indicative of the significant Norwegian reliance on large reservoir and storage schemes.

The general pattern shown here is that Norway has a greater emphasis on larger capacity schemes, whereas Scotland has more relative activity in schemes under 1MW. This split suggests there is a differing role for hydropower in the two countries that can be attributed to resource availability, but also the contribution of hydropower against a wider changing energy sector, as is the case in Scotland.

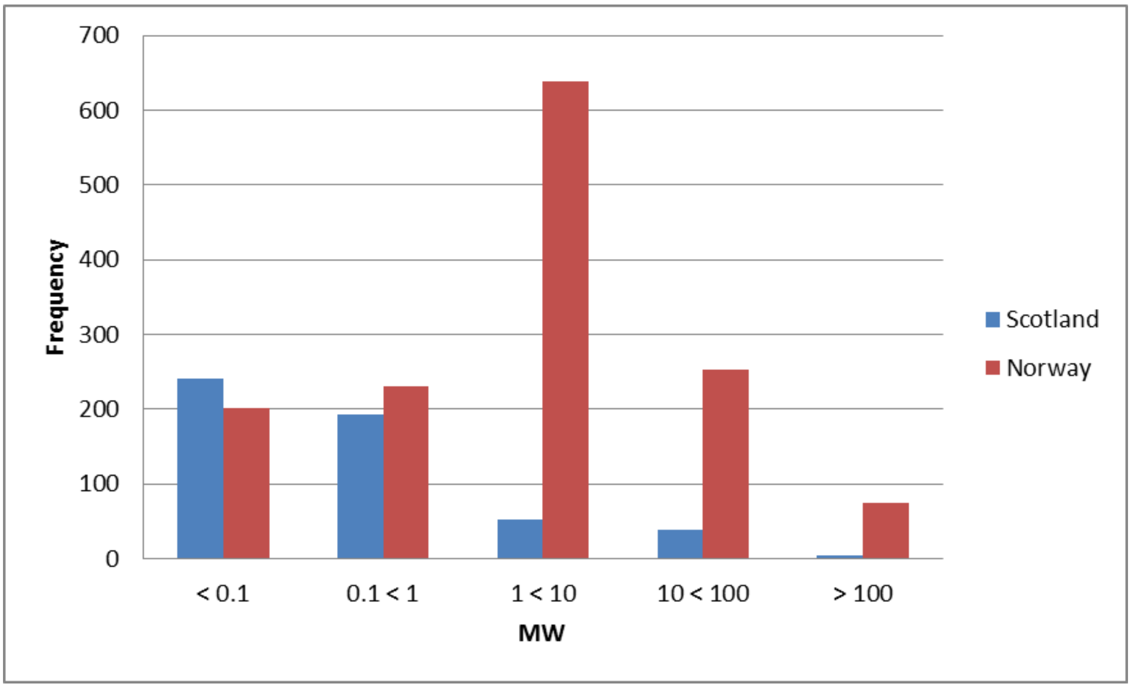


Figure 5.1: Scheme number by capacity group in Scotland* in 2012 and Norway in 2008**

(Source: *DECC, 2012d; Ofgem, 2013 **NVE, 2011)

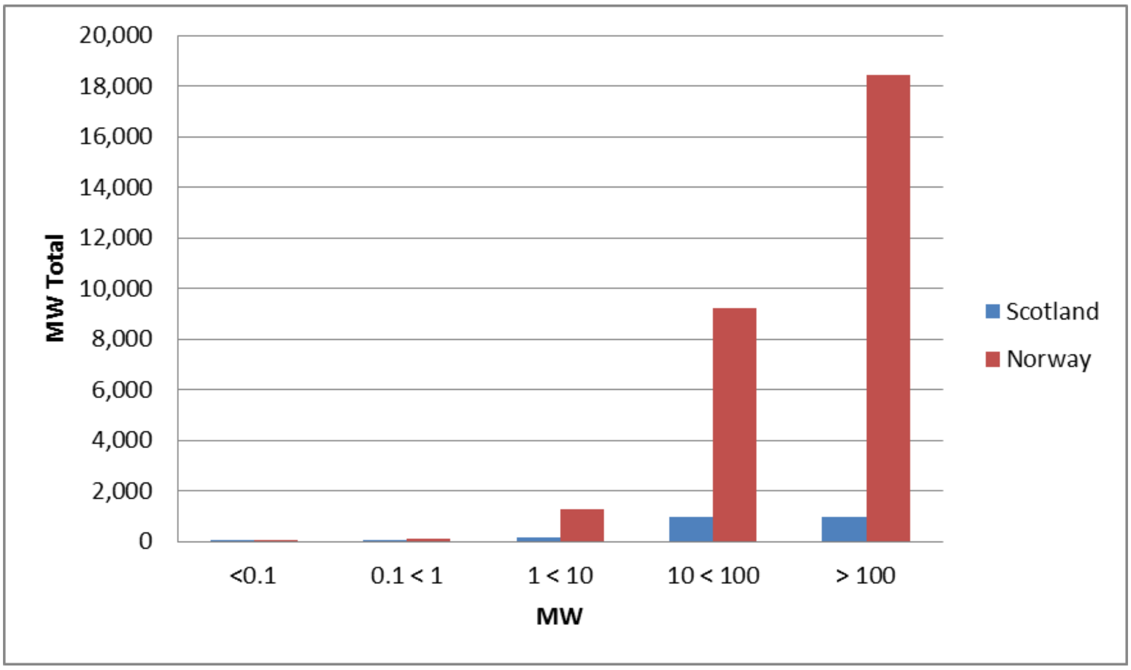


Figure 5.2: Scheme capacity by capacity group in Scotland* in 2012 and Norway in 2008**
(Source: *DECC, 2012d; Ofgem, 2013 **NVE, 2011)

So far through this comparative chapter we have clearly seen that Norway at 118TWh (IEA, 2011) has far more annual production from hydropower than Scotland at only 3.3TWh (Scottish Government, 2011). This contrast, however, is primarily reflective of the differing hydrological resource base. Indeed, Norway has an estimated technical and financial potential output of 205TWh, which after subtracting environmentally protected water environments leaves around 160TWh of viable output which could be developed (MoPE, 2008). Before applying local level environmental restrictions, Scotland has in the region of 6.1TWh when taking current output and adding technically and financially viable available capacity (Forrest and Wallace, 2009) at current load factors.

Therefore, of potential technically and financially viable national hydropower output, we can see Norway has developed 57% and Scotland 54%. When subtracting environmentally protected sites in Norway, the development percentage there rises to 73%: the equivalent figure for Scotland is not available. Although here we are comparing two different large scale resource mapping outputs, which come with different methodologies and assumptions, the magnitude of proportional hydropower development in the two countries, prior to applying environmental restrictions, is of a similar order. This picture seems to indicate that both countries have reached a similar point in their hydropower development trajectory, as a similar proportion of their total resource has been developed, and that any further development would be increasingly costly and sites less than optimal.

5.3.4 Hydropower trajectories in both countries

There are certainly similarities in the way in which hydropower emerged in Scotland and Norway. For example, in both countries a pioneering development phase in the early 20th century was initially triggered by an emerging industrial process with high energy demands, namely the electrochemical and fertilizer production industry in Norway, and aluminium smelting in Scotland. However, after this specific initial industrial and economic ‘need’ that hydropower was readily able to provide due to the climatic, topographic and hydrological resource base, subsequent continued uptake required a strategic, longer term commitment, delivered in both countries by the public sector. Periods of large development, namely 1943-1966 in Scotland and 1970-1986 in Norway, were driven by public sector policy, and indeed delivered as public schemes by government departments or agencies.

The North of Scotland Hydroelectric Board (NoSHEB), well documented by Payne (1988), came out of a political desire to develop the water resources of the Scottish Highlands with publicly owned hydropower schemes, alongside establishing a distribution network, to support the wider welfare, economic development and social improvement needs of the Highlands. The result was a centrally coordinated large-scale development programme, which maximised hydropower returns from the Highlands, with modest reservoir peak load sites near the industrial belt, and larger storage schemes in the North (Johnson, 1994). This development period came to an end in Scotland in the 1970s as conventional thermal and nuclear generation technology became more efficient and cost-effective, additional sites for hydropower became less economical (Payne, 1988), and environmental regulation become more stringent (Reid et al., 2006).

Hydropower development in Norway experienced a similar drop-off after 1990, with large schemes becoming controversial and ideal sites having been developed (MoPE, 2008), but this was only after more sustained development periods than seen in Scotland. Up until then, hydropower development remained central to national energy expansion policies, and did not have to compete as part of a wider, diverse energy mix, as seen in Scotland and the UK.

Although, as shown above, we see a similar development percentage of hydropower resources, due to the scale of resources in Norway and the central role of the technology for national energy needs, Norway has long since had to take a more strategic approach with hydropower development. The 1984 'Samla' Master Plan created a national strategic spatial system for hydropower regulation that allows proposed schemes to be considered against a series of tiered local level criteria that overlies environment and stakeholder value issues, with hydropower power resource viability. This early national mapping of sustainability criteria and resource availability guides development towards areas of low risk, and then triggers higher regulatory scrutiny where sites of higher conflict or sensitivity are pursued. A similar approach has only fairly recently been developed for specific regions in Scotland, such as the Loch Lomond and the Trossachs National Park, and Cairngorms National Park (LLTNP, 2012). There are also mechanisms that work more widely through the planning regime, to guide the correct kind of developments to the right locations, and to speed up licensing and prioritise regulatory resources (SNH, 2010b; 2011).

The above overview has shown that although there is a much higher resource potential in Norway, both countries have developed a similar proportion of their technically feasible hydropower resource. Norway, however, is shown to have a greater emphasis on large capacity schemes, whereas a greater proportion of hydropower in Scotland is under 1MW. There are various reasons for this distribution, such as those relating to the wider energy policy context. Norway, for example, requires a large contribution yet seasonal flexibility and balancing from generators, whereas hydropower in Scotland has more of a 'filling-in' role, providing capacity and storage capabilities where possible against the large base-load provided by fossil fuels. The characteristics of the available resource are also of importance, as Norway has close to 50% of Europe's hydropower reservoir storage capacity (Statkraft, 2009), which supports the increased emphasis on large schemes. Certainly, both of these elements are important, and the differing energy context and resulting demands upon hydropower shape the resulting characteristics of hydropower in the two countries.

Of the above Figures (**5.1** and **5.2)**, the available Scottish data (2012) is slightly more up-to-date than the Norwegian (2008), and so captures a recent large uptake in household and community level micro generation after the 2012 Feed-in Tariffs (FiTs) mechanism in the UK. This trend towards smaller level schemes is also seen in Norway (Knudsen and Ruud, 2011), and so forms a large part of the future development paths for both countries, alongside issues of scheme refurbishment and license reviews.

5.3.4 Current and future outlook for hydropower

With a similar initial uptake catalysed by an industrial need, further development through central public bodies, yet vastly different current characteristics and capacity, hydropower in both Scotland and Norway is presently at a similar point of development. It is also interesting to note that both countries have a similar outlook for the future. As achieving EU water policy objectives are often dependent on other policy areas, such as energy (Volkery et al., 2011), European standardisation in energy and water policy frameworks offers an interesting angle from which to examine how the wider context affects environmental decision making and issues of hydropower sustainability in both countries.

Whilst not in the EU, the European Economic Area (EEA) agreement grants Norway access to the EU's single market, in exchange for Norway adopting community legislation, such as that on energy and the environment. Although Norway is in a unique position delivering almost its entire domestic electricity needs through renewable generation, under the EU's Renewable Energy Directive (RED) (2009/28/EC) it still must meet a legally binding domestic target of 67.5% of *energy* use (including transport and heat) from renewable sources, which adds up to an EU wide target of 20% gross final consumption, by 2020. The UK is also subject to the RED, with its agreed EU target being 15%, though Scotland is aiming to exceed that and have an overall share of 30% (Scottish Government, 2011). Similarly, under the EU's Water Framework Directive (WFD) (2000/60/EC), both countries must also deliver protection and improvements to water bodies to ensure they achieve good ecological status by 2027.

With both countries subject to RED, and so looking to deliver renewable energy increases to meet national targets, whilst also implementing changes to protect and improve on water bodies as required under the WFD, Scotland and Norway currently face a number of shared regulatory pressures and context. These two high profile frameworks are significant for hydropower as they embody the challenge for hydropower governance to reconcile the renewable energy benefits with the tensions and trade-offs for river ecosystems (e.g. Reid et al., 2004).

There have been clear political signals in Norway that the era of large-scale hydropower construction is over, leaving development paths focussed on refurbishing and upgrading existing schemes and the construction of less controversial small scale schemes (Knudsen and Ruud, 2011). Similarly in Scotland, there are unlikely to be additional large schemes, due to environmental considerations and site availability (e.g. AEA, 2010; DECC, 2011b), with the focus on small and micro generation, and improving the operation of existing sites (Scottish Government, 2011).

This shared wider environmental policy context under the WFD has required regulatory bodies to review hydropower licenses in Scotland (SEPA, 2011b) and Norway (NVE, 2012). Additionally, given the wider renewable energy agenda, both countries are also revisiting storage and pumped-storage hydropower for its value in integrating increasing amounts of potentially intermittent renewable generation. It is in that context that Scotland is pursuing further pumped-storage capacity (AEA, 2010; SSE, 2012) and revising its current pumped storage operational approach in light of national needs, as shown at Cruachan in Chapter 3 above. In broadly the same manner, Norway is looking to respond to similar energy trends by building upon its hydropower storage capacity to serve wider European balancing needs, to act as a potential energy 'battery' for Europe (Solvang et al., 2012).

It is clear that whilst there are differences in the magnitude and characteristics of hydropower in Scotland and Norway, a similar developmental stage, and shared influences from EU governance frameworks, means that there are distinct similarities in the current and future outlook for hydropower in both countries. These current shared elements of license reviews under the WFD, and the regulation of small and micro hydropower offer two interesting and timely aspects with which to consider how the changing wider context for hydropower affects issues of sustainability.

Understanding the interaction of disciplines and scales is central to delivering a sustainable renewable energy system, especially as the UK and Europe move to ever increasing amounts of low carbon and renewable generation, and against a changing wider energy context.

5.4 HYDROPOWER RELICENSING AND IMPLEMENTING THE WFD

Due to the extent to which society utilises resources and services from the water environment, achieving EU water policy objectives is often dependent on other policy areas such as energy (Volkery et. al., 2011). In general among OECD countries, however, there is little harmonisation and insufficient consideration of the interrelation of water, energy and environment policy areas and frameworks (OECD, 2011). The result is often unsustainable outcomes and trade-offs.

A challenge for hydropower governance in Scotland and Norway is to reconcile the renewable energy benefits of hydropower with the tensions and trade-offs for river ecosystems (e.g. Reid et al., 2004). This need for balanced and sustainable hydropower decision-making is encapsulated in the requirement for both countries to meet binding renewable energy targets agreed under the EU's Renewable Energy Directive (RED) (2009/28/EC). RED promotes the exploitation of renewable energy resources such as fresh water systems, whilst also delivering protection and improvement of all water bodies under the Water Framework Directive (WFD) (2000/60/EC).

Finalised in 2000, the WFD requires Member States to achieve good ecological status, or good ecological potential for heavily modified water bodies (HMWB), across all surface and groundwater bodies by 2027. It forms a European-wide framework for establishing river basin districts, and a common six-year cycle of water body classification, objective setting, and monitoring for all individual water bodies across Europe. To deliver on the objectives for individual water bodies, Member States must apply WFD considerations to future water use proposals, but crucially also must review existing water use activities and licenses to secure improvements in ecological conditions. Changes to existing hydropower water use licence conditions are necessary to secure improvements in individual water bodies, and across wider River Basin Management Plans under the WFD. It is commonly accepted, however, that to deliver on these objectives, it is likely that there will be cases where there will be a reduction, or reallocation in water set aside for generation. The likely consequence will be a small decrease in electricity generation from hydropower.

5.4.1 Differing challenges for Member States?

The advent of the WFD created a standardised system across Member States for river basin management, and the classification and improvement of water resources. Although there is this regulatory standardisation, differences in factors such as environmental baselines, existing government frameworks, and national hydropower characteristics, mean that there is scope for variability in the approach and ecological outcomes from hydropower license reviews under the WFD.

As countries such as Scotland and Norway seek to reconcile the energy benefits of hydropower with its environmental trade-offs, understanding how differing characteristics and context affect this balance is central to delivering robust, sustainable decision making. Thus, whilst at a glance presenting regulatory standardisation, the example of license reviews under the WFD is a high profile example where we can fill a knowledge gap about how other, often external factors can affect environmental decision making and sustainability outcomes.

Through examining how the changing wider context for hydropower in Scotland has shaped its characteristics and outcomes for sustainability, this thesis seeks to explore the linkages and relationships between disciplines and scales, to inform the wider challenge of sustainable renewable energy. The specific issue of WFD implementation and hydropower licence reviews in Scotland is central to this challenge, as it is a 'pure' example of the need to reconcile energy and water environment needs. This section will critically examine the approach taken in Scotland, using the experience in Norway as a comparator. Whilst acknowledging the standardised framework created by the WFD, this section will focus on the reasons for and extent of differences in national implementation, examining how regulatory priorities and criteria are set.

5.4.2 Baseline for WFD implementation

i) Scotland

Under the WFD there are two river basin management districts in Scotland, providing the strategic vision and setting objectives for the individual water bodies. The *Scotland* river basin district is home to around 4.8 million people and covers an area around 113,920km^2 from the urban and industrial areas of Glasgow and Edinburgh in the south, to the culturally and economically valued landscape and water environments of the Highlands and coastal areas in the north. Pollution, abstraction and physical modification are the main water management pressures affecting WFD objectives in the district. Abstraction and flow regulation from electricity generation causes significant water management issues on 130 (1,141km) rivers and 45 (279km^2) lochs (SEPA, 2007), and impacts morphology on 86 (904km) rivers and 53 (298km^2) lochs (SEPA, 2007).

The *Solway Tweed* is the second river basin district in Scotland. It is home to a relatively rural population of 450,000 spread over the Scottish Borders and extending into parts of northern England. Its district covers an area of 17,500km^2 including the Tweed, Nith and Annan river catchments. The district includes the large Galloway hydropower development in the Dee catchment, as well as run-of river schemes. Here 11 HMWBs are designated due to the effects of hydropower, with early WFD characterisation showing that 60km of rivers are impacted by hydropower abstraction and flow regulation, and 11km^2 of lochs are significantly affected (Environment Agency, 2005). License revision measures will include updating compensation flows and freshets, and providing for fish passage at dams and weirs (Environment Agency, 2009).

As outlined previously, Scotland produces a maximum of 5TWh from hydropower per year, leading to approximately 70 water bodies being identified under the re-licensing process as being less than ecologically 'good' and adversely affected by hydropower (SEPA, 2011b). Hydrological impacts from hydropower range from highly artificial flow regimes downstream of abstraction, to the disruption of sediment transport and altered water body morphology due to large impoundments (Black et al., 2002).

ii) Norway

In comparison to Scotland's two areas there are 11 river basin districts in Norway, some of which are shared with Sweden and Finland. They range in area from 12,722 km^2 with 670 (59,631km) rivers and 324 (412km^2) lakes, to 68,291 km^2 with 1422 (58,542km) rivers and 661 (1519km^2) lakes (EC, 2012b).

Installed hydropower capacity in Norway is almost 30GW, generating 124TWh in 2010, equating to over 98% of national electricity consumption. With this level of development, and 85% of its HMWBs designated due to hydropower regulation, the scale and implications of license revision under the WFD in Norway is very significant. If restrictions in reservoir operation and minimum downstream environmental flow are applied to all 340 hydropower licenses that are open for revision before 2022, it would result in a loss of 5 to 12TWh per year, around 4 to 9.5% of national total electricity usage (NVE, 2012).

So whereas the WFD creates a standardised framework across the EU, of course when applied to member states' hydrological resources and hydropower characteristics, there is scope for a variety of different regulatory challenges and approach to environmental decision making. This dynamic is of value for this thesis as it considers how interdisciplinary, previously 'external' factors such as energy trends and policies can influence the environmental decision making and regulation of hydropower.

5.4.3 Designating HMWBs and setting GEP objectives

While setting the wider target of good ecological status (GES) for all water bodies, under Article 4(3) the WFD allows for a lower target of good ecological potential (GEP) for heavily modified water bodies (HMWB) that are regulated by valuable activities, such as hydropower. Although a standardised framework, the way a HMWB is defined and how the GEP is established are two key aspects that could result in differences in the way the Directive is interpreted and implemented in Member States. To reach the GEP objective in HMWBs under the WFD RBMP 15 year timetable, Member States must establish a programme of mitigation measures, and under Article 11(5) of the Directive this must include the revision of relevant permits and authorisations.

The WFD sets out that surface water bodies should be designated as HMWBs firstly when their hydromorphological characteristics have been altered substantially as a result of a valuable human activity. It goes on to add that HMWBs are established where to achieve GES would lead to a significant adverse impact on use, be disproportionately costly or technologically unfeasible, and the benefits of use cannot be provided by other means. Once designated a HMWB, a water body categorised in this way will have less stringent objectives in the RBMP.

5.4.3.1 Heavily modified water bodies (HMWBs)

In Scotland, a characterisation of river basin districts was finalised in 2005, from which SEPA identified water bodies as provisionally heavily modified or artificial. This process was based on assessments of the risk that the hydromorphological alterations from valued activities such as flood protection and electricity generation were substantial enough to prevent GES being attained. After this initial overview characterisation work the water bodies were assessed in detail, and checked back against the WFD criteria more closely. The key criteria were, that a water body's hydromorphological characteristics have been altered as a result of human activity, that improvements to these characteristics would have a significant adverse impact on use, and the benefits provided by the use cannot reasonably be achieved by other means (SEPA, 2008).

The initial scoping criteria for HMWBs used in Norway identified those water bodies that are subject to human intervention and use, which has resulted in significant hydromorphological changes that prevent the water body from achieving good ecological status. HMWB status was then finalised upon further evaluation of the value the modification has to wider society, and the potential for mitigation measures (EC, 2012b).

5.4.3.2 Good ecological potential (GEP)

The approach taken in Scotland for classifying the ecological potential for HMWBs is based on the 'alternative approach' agreed between the European Commission and Member States under the WFD. To set the GEP, this methodology identifies firstly a *maximum* ecological potential (MEP) set at the point where all mitigation options are in place, and the water body is at the maximum hydromorphological quality possible given the constraints imposed by the use activity (SEPA, 2008).

GEP represents an ecological quality only slightly lower than the MEP the water body could achieve. Accordingly, a water body is identified as being at GEP if all mitigation is in place except that expected to deliver only minor additional ecological benefits. Therefore a HMWB at GEP, or better, is one where all relevant mitigation measures for specific impacts have been taken, except those which:

i) are not practicable given the characteristics of the water body;

ii) have a significant impact on use; or

iii) have a significant adverse impact upon the wider environment (UKTAG 2008).

The equivalent process in Norway for setting the GEP also firstly involves a determination of the environmental conditions of a water body. Potential mitigation measures for that water body are then assessed, utilising a nationally developed list of options that specifies their objectives and costs, and which are available instruments that can be delivered by a revision of terms or a legal mechanism. The measures must not result in a significant adverse effect on total electricity production, or peaking capacity, and must have no significant adverse effect on the wider environment, such as habitat, species, and cultural and recreational value. Against these constraints, the ecological effects of the measures are then considered, and the GEP is defined as the resulting ecological outcome of all applicable measures (Halleraker et al., 2009)

Rather than vast differences, this brief overview of HMWB and GEP definition and designation in Scotland and Norway shows many similarities. So despite the significant differences between the two countries in terms of the national energy role of hydropower, and the scale and characteristics of the hydropower resource itself, the interpretation and implementation of these WFD elements is very similar, showing a similar regulatory philosophy and approach. Both countries carry out a form of risk scoping for HMWBs, identifying water bodies exposed to valued activities. This scoping is followed up with case level assessments of the value the modification has to wider society, and the potential for mitigation measures. The key feature for GEP setting for HMWBs with substantially altered character in both countries revolves around establishing the level of mitigation that maximises hydromorphological conditions, but at the point that is not overly costly in financial terms and does not have a significant adverse impact on use.

Perhaps as is to be expected under the standardised WFD, this comparison presents strong uniformity in approach between these two countries. In both cases, however, it leaves an additional emphasis on the remaining variable of significant adverse impact on use. Given the differences in hydropower characteristics between the two countries, fulfilling the common goal of avoiding significant adverse impact on use could therefore present distinct approaches and challenges for both regulatory frameworks.

5.4.4 Significant adverse impact on use

In assessing whether a measure has a significant adverse effect on use, the extent to which the measure reduces the yield or impairs the service should be assessed. As is the case with the renewable benefits from hydropower, the wider environmental benefit of the use should also be considered (UK TAG, 2008). Under the relicensing agenda in Scotland, SEPA (2011) will not require improvements to the water environment if reductions in hydropower generation at a scheme level, or cumulatively at a national level are significant. The significance of the reduction in electricity generation will be determined through a consideration of the:

i) impact of potential reduction on the hydroelectricity scheme concerned;

ii) cumulative impact on hydropower generation within the RBMP cycle;

iii) significance of the benefits expected to result from the improvement to the water environment enabled by the reduction (SEPA, 2011)

The key aspects of 'use' are deemed to be the output from a scheme, or cumulatively across the hydropower sector, and whether specific benefits to the water environment are significant enough to be justifiable against this. In considering these cumulative aspects of impact on use, SEPA (2011) has set the aspiration to keep losses in generation output to under 2% of current output volume, which with the total annual contribution up to 5000 GWh, is around 100GWh.

Against binding EU-wide renewables targets, and the domestic aspiration for Scotland to generate the equivalent of 100% of electricity consumption from renewables by 2020, renewable generation is set to increase in Scotland. At present, however, as this trend is principally driven by technologies such as onshore wind, which under a moderate uptake scenario could rise from 5TWh per year currently to 17TWh by 2020 (Scottish Government, 2010b), any generation losses in hydropower under WFD license reviews will be an increasingly small proportion of the wider renewables contribution. Indeed, due solely to the increase in other technologies, the contribution from hydropower is projected to decrease from around 30% of renewable output in 2008, to 10% in 2020 and around 7.5% in 2030 (Scottish Government, 2010b).

In this changing wider energy context, it is logical therefore for SEPA to work with operators to identify opportunities where scheme licensing can be updated without any, or insignificant generation losses, or that can be balanced elsewhere, but also to delay or 'back-load' the changes that would result in output losses. Indeed, SEPA (2011) propose that the majority of the cumulative output reductions come in the third river basin planning phase from 2021 to 2027. This presents an interesting dynamic characteristic for sustainable renewable energy in Scotland, where, as increasing amounts of renewable capacity is established across all technologies, through the above relationship, this will result in improved water environment conditions. In the context of this thesis, we can see how the future state of the water environment conditions in Scotland nationally, or even at specific threshold sites, is tied to the wider development of renewable generation capacity.

As highlighted in Chapter 4, the eligibility criteria for financial support under the 2002 Renewables Obligation (Scotland) (RO(S)) extends to hydropower schemes under 20MW that have been constructed or renewed since 1990. It should be noted that these renewed schemes are not a small proportion, but account for the majority of hydropower capacity under RO(S) mechanism, some 364MW (61%) (Ofgem, 2013). This eligibility creates a synergy with the relicensing process, as existing schemes are given support for the renewal of generation infrastructure, resulting in increased operational and potentially environmental efficiency. In other words, the RO(S) as an energy policy creates a positive incentive which also serves delivery of the WFD, a separate environmental policy. Distinct from this, by supporting the construction of additional eligible capacity at existing schemes - such as in the form of compensation set (CS) turbines - the RO(S) mechanism also provides an avenue for generators to recoup potential generational capacity lost elsewhere due to improvements in environmental flow. The example of the 7.5MW Fasnakyle CS also demonstrates that these additions are able to better optimise the statutory compensation flow release, add extra capacity, and yet provide little iterative impact and stakeholder objection (Scottish Government, 2004).

5.4.5 Applying the experience in Norway

Due to the way in which energy policy affects the potential to achieve water policy goals, there are often calls for greater integration between the two policy areas to minimise sustainability trade-offs (OECD, 2011). Whilst it is far from full integration, this setting of the WFD relicensing work in Scotland in the context of the wider energy agenda is important to deliver integrated, sustainable decision making for hydropower. This dynamic for Scotland reaffirms that it is not practical or appropriate to set a common EU threshold for the significance of impact upon hydropower, due to the differing energy and environmental context in Member States, and that in fact there is a degree of domestic political judgement needed in the process (Kampa and von der Weppen, 2011).

As hydropower produces over 98% of electricity demand in Norway, the move to place hydropower environmental decision making in the context of wider energy needs is even more important as even a small percentage reduction in total hydropower capacity is significant for national supply. Furthermore, as we have seen, the Norwegian hydropower sector is dominated by large reservoir storage schemes that utilise upland spring snow melt to serve the following increased winter demand needs, and balance potential inter-annual variability in precipitation input. Consequently, as regulated reservoirs account for 80% of hydropower production in Norway, reservoirs are central to national security of supply (MoE, 2012). In addition to potential losses of capacity, this resulting national reliance on the balancing role of hydropower in Norway therefore creates a further sensitivity to the WFD intervention that can heighten the 'significance' of impact on use when considered against environmental gains. Loss of balancing capacity has consequently been identified explicitly as significant adverse impact on use, meaning measures that address reservoir operation and compromise electricity production and reservoir capacity cannot be justified (MoE, 2012).

The SEPA (2011) consultation document sets out the regulatory approach for significant adverse impact on use in Scotland. It also poses a number of questions for stakeholders regarding the approach taken. These elements provide a basis for comparison with Norway.

The Scottish approach weighs the significance of impact by considering the magnitude of generation loss at a scheme level and the national cumulative impact within the RBMP cycle, against the significance of expected benefits to the water environment (SEPA, 2011). Similarly in Norway, scheme level generation losses are also considered on a case by case basis (Ibrekk, 2008), but this is alongside explicit consideration of loss of storage and balancing capacity (MoE, 2012).

As discussed above, SEPA (2011) has set a 2% maximum generation capacity loss as a national pre-set baseline figure for the whole sector, as a proportion of current maximum annual output. There has not been an equivalent threshold set in Norway, but it has been calculated that 4 to 9.5% (5-12TWh) of annual output would be lost if minimum environmental flow and reservoir operation restrictions were applied to all 340 reviewable licenses before 2022 (NVE, 2012). This is deemed to be an unacceptable impact on use, and has led to the alternative development of an increased strategic approach in Norway.

The Norwegian government has conducted a national screening review to characterise, rank and prioritise the renewal of hydropower licenses under the Watercourse Regulation Act that may be revised before 2022. The screening process will generate a priority list for water courses or river basins where environmental improvements can be achieved with least cost to generation output or balancing capacity, or where reduced generation may be acceptable due to significant environmental gains. Opportunities for production and efficiency gains are also then investigated, through the expansion and upgrade of existing infrastructure or alterations to generation practices (NVE, 2012). The potential for climate change to change the inflow for hydropower in Norway is also considered as part of the revision process, as it has the potential to alter total annual reservoir inputs, and also their seasonality of distribution (MoPE, 2012).

Scotland has not conducted a national screening hierarchy exercise of this nature, but does of course address water body improvements through river basin management plans, and overall has set a strategic aspiration to cap generation losses to 2%. Whilst a screening review could also be of value in Scotland, due to the smaller number of hydropower schemes it is often clear to regulators which stations and water bodies need to be targeted for revision. Being perhaps more agile and responsive as a result, the focus for regulators in Scotland is often on collaboration, building consensus and overcoming potential conflict between stakeholders regarding changes to scheme operation and water resource characteristics. Indeed, proposals for varying licenses that suit generation and downstream needs are often in the first instance made by generators themselves, as was the case with the Tummel, Conon, and Ness hydro schemes in the first round of RBMPs (SEPA, 2010b).

5.4.6 The role of energy and environmental needs in relation to license reviews

The WFD created a standardised water governance framework across Europe, to achieve good ecological status (or potential) across all surface and ground waters by 2027. Encapsulating the challenge of hydropower governance to reconcile the benefits of hydropower with the trade-offs for river ecosystems (Reid et al., 2004), revising existing hydropower licenses is needed across all Member States to deliver local environmental improvements whilst avoiding adverse impact on use.

It is commonly understood that the environmental implications from hydropower are shaped by existing local hydrological conditions (e.g. Gilvear et al., 2001; Marsh and Anderson, 2001), and scheme design and operational characteristics (Petts, 1984). These local environment and energy characterises in turn determine the challenges for regulation as it seeks to reconcile potentially competing policy objectives, and deliver sustainable renewable energy. It follows that scheme level environmental decision making should consider site habitat and environmental sensitivity (e.g. Demars and Britton, 2011), value and service provision (e.g. NEA, 2011), but also the characteristics, operational profile and downstream flow implications of the scheme itself (e.g. Acreman et al., 2009; UKTAG, 2013). This comparison between WFD license revision in Scotland and Norway, however, has highlighted the importance of additionally considering the wider energy context, because in reality site specific environmental decision making, and in turn local level ecological outcomes, are influenced by a wider energy agenda and context.

The WFD has created a standardised water governance framework across Europe, which Scotland and Norway have interpreted and implemented in a similar manner with reference to issues of HMWBs and GES. However differences arise in the approach and delivery of localised ecological improvements in water bodies, due to the national characteristics, context and needs of the wider energy system. In the case of Scotland, we can see for example how growth in generation output from other renewable technologies reduces the proportional contribution of hydropower, arguably making ecological gains through generation losses more acceptable over time. Similarly, in Norway, the heightened reliance on reservoir storage for national energy integrity means that reservoir or downstream ecological targets or objectives that could be achieved in other WFD Member States, are not justifiable in Norway.

The case of license revision has highlighted that effective contemporary water regulation has had to develop and expand its scope to consider this broader energy context and mechanism. Thus we see a further development 'phase' in the scope of hydropower regulation to that set out in academic literature, such as by Reid et al (2004; 2005). Building upon this body of work, we now see that after the early 20th century protection of private water and fisheries rights (Reid et al., 2002), the slightly broader scope including wider aesthetics and fisheries concerns of NoSHEB (Black et al., 2006), and the modern European led consideration of numerous habitats and species seen today, there is now a new phase where the consideration of national and even EU level energy context and needs is key.

Hydropower relicensing in Scotland and Norway is examined here as it is a prominent example of the way in which water regulation must balance site energy benefits with impacts on the water environment. This investigation has illustrated that in fact national energy considerations play a role in the delivery of the WFD, scheme level decision making, and local level ecological outcomes. Indeed, it seems that to deliver effective hydropower regulation, environmental agencies must be increasingly aware of the wider energy agenda, and beyond that the changing national context and needs. In this way, this investigation has demonstrated:

- The changing national characteristics and role of hydropower in the wider energy mix must be reflected and integrated into relicensing and environmental decision making to inform issues of acceptability.

- Integrating these wider energy characteristics can work to overcome a wider policy disconnect between water and energy domains, and reinforce the sustainability of renewable energy.

- Growth in national capacity of other technologies will make further environmental improvements in regulated water bodies more acceptable, and delivery of the WFD more readily achievable

- The delivery of environmental improvements in regulated water bodies under the WFD is tied to the changing role and characteristics of hydropower, the growth of capacity in other technologies, and the wider energy context.

This thesis seeks to inform the ever evolving challenge of sustainable renewable energy by exploring the linkages and creating dialogue between disciplines and scales. Through the example of incentive mechanisms, Chapter 4 demonstrated how wider energy policy can shape scheme level decision making, and in turn affect environmental outcomes, meaning regulation often has had to respond to a changing energy agenda.

A similar effect is occurring here with regards to license reviews, where the environmental decision making and local level habitat improvement are influenced by a wider energy agenda. However, environmental decision making and outcomes here are not just reflective of specific energy policy, as was the case with incentive mechanisms, but additionally the national role and characteristics of hydropower, and energy trends and needs more widely.

This comparison of license reviews in Scotland and Norway has shown the mechanisms by which wider energy context shapes decision making regarding water environment improvement, thus indicative of the way in which achieving water policy objectives are dependent on other policy areas such as energy (Volkery et al., 2011). Although there is little harmonisation at a European policy level (OECD, 2011), this research shows that Member States' regulatory systems need to consider their differing national, and sometimes the international, energy context to overcome issues of policy isolation, to build harmonisation and deliver sustainable renewable energy in a changing world.

5.5 HYDROELECTRICITY AND ENVIRONMENTAL MITIGATION

Central to the challenge of sustainable hydropower is the role of mitigation in reducing impacts and trade-offs for valued social, economic or environmental aspects. Often targeted at protecting specific elements, mitigation can make a scheme more acceptable in terms of regulatory approval and licensing, but also wider stakeholder perception. Since the emergence of impoundment schemes, the challenge for water managers has been to utilise available water resources, whilst also supporting these additional societal goals (Richter and Thomas, 2007). The characteristics of hydropower in Scotland and Norway are shaped by its historical emergence, resource availability and continuing national energy agenda. Similarly, as social, environmental and political priorities are often changing and evolving, mitigation has to evolve and adapt, leaving the potential for existing infrastructures and approaches to be below optimal against contemporary needs.

5.5.1 Mitigation trajectories and characteristics

Critically examining the historical emergence and changing application of hydropower mitigation in Scotland, using Norway as a comparative element, provides an avenue to examine the sustainability of hydropower in Scotland now, and into the future. It also works to consider how the mitigation trajectories and outcomes are shaped by changing debate, stakeholder intervention and a wider governance context. This work fits in with the wider aim of this thesis to inform the challenge of delivering sustainable renewable energy, in a changing world. This section will seek to address questions such as:

- How did mitigation emerge and develop in the two countries?
- How has debate and stakeholder dialogue shaped mitigation trajectories?
- How do current mitigation characteristics between the two countries differ, and why?

- What is the role of the changing wider context in shaping mitigation characteristics?

This section will first consider the changing application of mitigation in Scotland over the various periods of development, using the Strathfarrar-Kilmorack scheme to examine the specific approaches taken in more detail. It will then consider how the mitigation approach has developed in Norway, and then provide a comparative discussion.

The literature review in Chapter 2 above sets out academic understanding of the influence of hydropower on the water environment, but also touched upon work on the changing application of compensation flows (e.g. Gustard, 1989; Black et al., 2006) and the development and increasing scope of hydropower regulation in Scotland (e.g. Reid et al, 2004; 2005). To avoid repetition, this present evaluation will avoid overly restating what is covered in Chapter 2, but through this current study of mitigation trajectories in Scotland will apply and build upon it, through the examination of some recent examples and the comparison with Norway.

5.5.2 Natural flow variability

The 'natural flow regime' paradigm recognises the critical role natural flow characteristics and variability have in supporting freshwater ecosystems and their integrity (Poff et al., 1997; Poff and Zimmerman, 2010). An alteration to the natural flow profile, away from this equilibrium, therefore leads to a response in downstream physical, chemical and ecological characteristics (Petts, 1984). The pervading effects of hydroelectricity impoundment schemes are commonly the reduction in downstream flow (Richter and Thomas, 2007), habitat fragmentation, and the disruption of key ecological flow variability (timing, frequency, magnitude, rates of change) (Petts, 1997), which form flow needs or 'building blocks' to support ecological integrity (UKTAG, 2013; King et al., 2008).

Reflecting the cascading influence of flow alteration through the freshwater system, the associated impacts can be grouped into three 'orders' (Petts, 1987). Firstly, there are the initial barrier and input changes (i.e. flow regime and sediment); secondly, change to habitat, channel form, substrate composition and macrophyte population; and thirdly, a wider fish, invertebrate and biotic population response. This perspective is useful as it underlines the influence of the changing inputs, provides a form of categorising of effects, and presents the temporal and spatial chronology of impacts necessary to begin to consider mitigation and restoration goals in policy and practice. It can also be used as a means to assess critically the objectives and appropriateness of previous approaches to mitigation, and how they have developed over time.

In part, the application of mitigation has also been influenced by the historical development of understanding regarding the impact of hydropower operation on water bodies themselves. Prior to 1950, although there was an awareness by engineers of the potential for temporally and spatially localised channel degradation, there was little field data on the impacts of large schemes, as they were somewhat rare at the time. Following a significant increase in the rate of large dam construction from 1950, in addition to the development of scientific measurement and process studies, which became pervading features of fluvial geomorphology research (Petts and Gurnell 2005), there was a greater appreciation of the temporal and spatial extent of impacts on water bodies in the scientific literature (Brandt, 2000). In addition, however, as this section will also consider, mitigation is also characterised and shaped by changing stakeholder influence, governance structures, and environmental priorities.

5.5.3 Historic Scottish hydropower, mitigation and compensation flows

With an enviable hydrological resource base, Scotland has a long history of hydrological alteration (Gilvear, 1994), including large hydropower development phases in the early 20th century principally against the background of an emerging aluminium industry (Reid, 2002), to a greater degree under the North of Scotland Hydroelectricity Board (NoSHEB) from 1943 (Payne, 1988), and more recently under the renewables agenda. This developmental trajectory has also been accompanied by 'phases' of development in the scope of hydropower regulation and mitigation (Reid et al 2004; 2005), driven by changes in governance context, stakeholder influence, and scientific understanding,

5.5.3.1 Pioneering hydropower phase

Firstly, supporting the aluminium smelting industry in the 1920s, private schemes such as at Kinlochleven (24MW) and Lochaber (64MW), with large storage reservoirs, hydrological alteration and a high load factor, base-load generation (Payne, 1988), had little environmental flow mitigation (Reid, 2002). Schemes were promoted by private individuals and companies, authorised by Private Acts of Parliament, and as was the case at the Lochaber scheme, controls on water flows and levels were for the benefit of a private landowner, and weir regulation was imposed solely to maintain fisheries access. The Grampian scheme from this period additionally only allowed abstraction when flow exceeded a certain threshold, a minimum outlet release limit was stipulated, and for the first time seasonal freshets to aid fish spawning were mandated (Reid et al., 2005).

In this period there was certainly no consideration given to wider environmental protection or ecological functioning, as flow mitigation goals were aimed at meeting the needs of individual private land owners, and to protect salmon fisheries in terms of maintaining seasonal spawning, but also ensuring fisheries access. Having no mitigation towards wider ecological integrity and functioning, certainly when compared with the prominence of private and salmon interests, was due in part to the narrow scope of regulatory protection (Reid et al., 2005), but also arguably because there was no stakeholder body that represented those interests. A central theme to the mitigation in this period was the focus on longitudinal connectivity within the water body, relating to the passage of salmon, reflected through freshets, and salmon ladders such as at Pitlochry. With the study of impounded rivers emerging through the field of engineering, and also in this period considering issues of channel degradation and reservoir sedimentation, the issue of fish migration certainly predates issues of water quality and ecological elements (Petts, 1984), that came later with the emergence of fields such as hydrology and ecohydology studies. We can see, therefore, how the stakeholder influence and the dominant academic understanding in this period shape the orientation and characteristics of mitigation.

5.5.3.2 Flow consideration of the NoSHEB phase

Following the 1943 Hydro-Electric Development (Scotland) Act, the NoSHEB period of development brought a changed system of governance, where constructional orders were presented by NoSHEB, then approved by ministers. Under the Act, NoSHEB was required to have regard to scenic, architectural and historic elements, and also as far as possible to avoid injury to fisheries and to the stocks of fish in any waters (Reid et al., 2004). Overseeing committees on fisheries and amenity were also established that made recommendations to NoSHEB, and the Secretary of State if they felt necessary. This regime meant that the balance of interests remained the same as before 1943, and accordingly mitigation took a similar approach (Reid et al., 2004). Although NoSHEB flow provisions became more sophisticated, they still did not serve any wider ecological purpose as before, but were mainly for the benefit of salmon fishing interests, principally due to the influence of the oversight from the Fisheries Committee and the local District Salmon Fisheries Boards (Black et al., 2006).

When applying the mitigation approach taken in these early pioneering and NoSHEB phases of development to Petts' (1987) orders of impact framework, we can see that the impacts being considered are very much 'first order' impacts, such as the initial physical barrier effects. This highlights that the scope of the impacts considered in these periods, and consequently the resulting mitigation approach, are limited in their appreciation of the fuller implications from hydropower. This position demonstrates that despite the large political and mitigation focus on salmon interests, there is still scope for more complex 'third order' impacts on these valued species and populations through 'second order' habitat, channel form and macrophyte change.

Previous work by Black et al. (2006) provides an overview of the extent of and basis to compensatory flow provision amongst 26 NoSHEB schemes. The survey of Constructional Agreement documents finds that above a 20km^2 catchment area threshold, high proportions of compensatory flow are provided, often generously in excess of Q_{90} especially on salmon rivers. For the schemes a variety of flow provision types are prescribed, with constant discharge, then seasonally varying discharge being most common, followed by constant or seasonal flow alongside a freshet or block grant.

5.5.3.2.1 Revisiting the NoSHEB Strathfarrar-Kilmorack scheme

The 1962 NoSHEB Strathfarrar-Kilmorack scheme in the western Highland of Scotland provides an example of a hydro development from this period that is located on an important salmon river-system. Forming the northern section of the wider Affric-Beauly development, the Strathfarrar-Kilmorack scheme is a fairly simple hydropower system, with upstream abstraction from the linear Lochs Monar and Beannacharan serving power stations at Deanie (38MW) and Culligran (19MW) respectively, followed by in-river generation downstream on the River Beauly at Aigas (20MW) and Kilmorack (20MW).

The Strathfarrar-Kilmorack Constructional Agreement formally sets out the river and flow provisions accompanying the scheme's approval, and again is very much reflective of the desire to protect salmon interests. At three dams within the scheme there were explicit requirements to 'provide for the passage of fish' (NoSHEB, 1958), for which Borland fish passes were constructed at Beannacharan, Aigas and Kilmorack. Compensatory flow provisions mandated in the agreement state sufficient water had to be released year-round to specified sites to maintain (or exceed) a stipulated average daily volume in million gallons per day (mgd). These prescribed minimum daily volumes, ranging from 20 mgd in the upper reaches to 250 mgd in lower reaches, would in themselves, for example, have allowed for significant flexibility in release profile. Specifically, by only stipulating a minimum threshold for daily volume, this still permits vast and potentially extreme variability in discharge and short term rate of change. This potential flexibility is a pattern shared in other NoSHEB Constructional Agreements, which leads to the suggestion that additional detail and minimum *rates* of flow would have been introduced subsequently to these approvals (Black et al., 2006).

It has up to now not been within the scope of studies to consider additional NoSHEB agreements beyond the formal Constructional Agreement documents, although the potential for a further level of detail in flow agreement has been acknowledged (Black et al., 2006; Reid et al., 2006). Documentation in the Berry Papers collection held at the University of Dundee archives regarding the Strathfarrar-Kilmorack scheme, however, does indeed show that an additional level of detail was made in the compensation agreements, beyond that reflected in meta studies undertaken previously.

Table 5.2 summarises the agreements set out in the Constructional Order (NoSHEB, 1958), and also this additional level of information on historical compensatory flow provision (NoSHEB, 1969; 1969a). Rather than solely presenting the previously seen daily flow allocation (million gallons per *day*) that is seen in the constructional order (NoSHEB, 1958), which could be satisfied with wholly ecologically unsustainable release profile, this later documentation from the 1960s (NoSHEB, 1969a) shows 'hands off' compensation threshold agreements were created through stipulated minimum flow volumes. Specifically, it records a mandated release of 85 cusecs (cubic feet per *second*) from the Beannacharan Dam, in addition to a minimum flow of 222 cusecs immediately below the Culligran Power Station.

Seasonal freshet releases are also defined further for the upper Farrar, with an annual allocation provided at the confluence of Uisge Misgeach and the Farrar of 2000 m.g., to be released as a ‘steady flow’ of 70 cusecs (38 mgd) for 53 days. Additionally, in the lower Farrar an annual allocation of 3000 m.g. is to be released from Beannacharan Dam as a freshet of 184 cusecs (100 mgd) for three consecutive days per week, for 10 weeks starting in mid August. These provisions however still fall short of seeking to encourage adequate variability in flow regime for this scheme to support wider freshwater ecosystem functioning.

Table 5.2: Mandated low flow and freshet levels stipulated by site, for the Strathfarrar-Kilmorack scheme, as at 1969

Location	Flow allocation (per day)*	Minimum flow volumes **	Freshet allocation (per year)*	Freshet flow volumes**	Fish Pass in place?
Uisge Misgeach (at confluence with River Farrar)	30 mgd		2000 m.g.	70 cusecs	
Uisge Misgeach (upper reaches)	20 mgd				
Beannacharan Dam	45 mgd	83 cusecs	3000 m.g.	184 cusecs	
Culligran Power Station	120 mgd	222 cusecs			Yes
Aigas Power Station	250 mgd				Yes
Kilmorack Power Station	250 mgd				Yes

Sources: *NoSHEB (1958), **NoSHEB (1969; 1969a)

5.5.3.2.2 Unpacking the Strathfarrar-Kilmorack flow agreements

In revisiting these early flow agreements it is hoped that a greater comprehension of the motivations and decision making process can be gained. Set against the present legacy and challenges of hydro in Scotland, this comprehension can be used to understand better the long term implications of certain approaches, context and specific decisions. Nevertheless, pinning down the scientific approach taken in relation to the setting of compensatory flows for the NoSHEB schemes remains somewhat elusive. Evidence of the details behind decision-making is fragmentary (Black et al., 2006), and there are few clear statements existing as to what the objectives of certain flow policies were, and why other approaches were not explored.

The historical development of the knowledge and application of compensation and environmentally sensitive flows has been explored by some scholars (e.g. Risbridger, 1962; Gustard, 1987; Gustard et al., 1989). Their work shows that as early as 1921 the Water Power Resources Committee in the UK was seeking to move away from a general approach for compensation waters allowance (such as a 1/3rd to 1/4th of total river flow rule raised previously), and recommended that due regard should be given to a river's natural variation of flow (Risbridger, 1962). This finding suggests there may have been an appreciation of wider environmental flow in the UK earlier than would be expected.

As mentioned, research into the implications of river impoundment began to emerge and develop following the proliferation of the schemes themselves (Petts and Gurnell, 2005). The emergence of specific research themes in academic literature concerning impounded rivers also has a historic profile, as presented in **Table 5.3**. It is notable that in 1958, at the time when the Strathfarrar-Kilmorack scheme was approved, the issue of fish migration and connectivity was established as an important theme in river impoundment studies, which is borne out in the scheme, indicating that the timing of a scheme's development is key in determining the nature of mitigation measures adopted. As a side note, it is of course unclear if this scientific agenda led to increased debate and uptake of fish migration as an issue for hydro, or if restricted migration was an issue readily perceived and valued by stakeholders, given the significant Scottish and local economic dependence on the salmon industry, so led to its uptake as an issue in scientific research.

Table 5.3: The emergence of specific themes in impounded rivers academic literature (Adapted from Petts, 1984)

Year	Themes
1930	Channel degradation
	Reservoir sedimentation
1950	Fish migration
1960	Water quality
1965	Channel form
	Plankton
1970	Aquatic vegetation
	Benthos
1975	Riparian habitats

As discussed earlier, there are three main components to the mitigation measures for the Strathfarrar-Kilmorack scheme, those being; (i) the maintenance of a 'hands-off' low flow; (ii) the provision of seasonal freshet releases; and finally, (iii) fish passes, all limited to specific, strategic sites on the river network. If we consider these measures solely against this connectivity debate and context, notwithstanding other issues such as perceived aesthetics; it could be legitimately argued that each seeks to serve salmon migration objectives in some way. Addressing each in turn, the underlying connectivity objective would be as follows:

i) **Hands off, low-flow** - Provision of an adequate minimum body of water for salmon viability;

ii) **Freshets** - Encouraging seasonal spawning and river running;

iii) **Fish passes** - Enabling the physical migration past artificial barriers and facilitating seasonal longitudinal migration of populations

On numerous occasions Fisheries Estates on the affected river network raised issues with the Hydro Board. Matters raised included salmon not running the Farrar in quantities comparative to before hydro construction; salmon observed to be trapped between the Kilmorack and Aigas Dams; and instances of smolts inadvertently passing through turbine intake screens (NoSHEB, 1971a; 1971b). Indeed, the setting of the mitigation flow here itself appears to be stakeholder led, as representatives of the Lovat and Nairn Estates themselves were tasked with determining 'optimum' freshet timing and duration which they subsequently communicated to the Generation Engineer following inspections in 1963 of the stretch of the Farrar between Beannacharan Dam and Culligran Power Station (NoSHEB, 1969a).

A key critique of this early regulatory framework has been aimed towards the lack of a formal mechanism to 'review and revise' flow agreements, to maintain their efficiency against a range of shifting social and environmental flow variables, whilst additionally adding responsiveness to future change (Reid et al., 2004; 2006). Allowing for the assumption that flow agreements were 'optimum' to begin with, these archival sources hint at compensation waters continuing to be 'subject to variation from time to time because of river conditions' (NoSHEB, 1969a). This suggests that a certain amount of flexibility was applied, albeit only based upon local stakeholder needs in this instance, rather than changing wider regulatory goals.

The above flow provisions clearly display that salmon migration and connectivity are central concerns in debate regarding the impact of the scheme. Given the uncertainty regarding the underlying decision making by NoSHEB (Black et al., 2006), however, further information on the objectives of certain flow policies, or why other approaches were not explored, is useful. Further archival material begins to shed additional light on this question through a number of statements from NoSHEB regarding compensatory flows on the Strathfarrar-Kilmorack scheme. Specific reference by the Hydro Board was made in a 1969 letter stating that wider angling was 'not a consideration', as it had been addressed through financial compensatory payments and a Public Inquiry. Furthermore, they point out that the compensation flows of the River Farrar were provided solely to 'encourage fish to ascend to the areas suitable for spawning' (NoSHEB, 1969b).

It is clear that this very narrow scope for environmental governance would not be permissible today (Black et al., 2006). Indeed, the maintenance of natural patterns of longitudinal connectivity, as shown here, alongside lateral connectivity, are seen as only one of four ways in which flow regimes (and their change) can support (or undermine) aquatic biodiversity. Namely, this outlook does not consider physical habitat maintenance, aquatic species' life cycle patterns, or engage with the viability of species introduction (Bunn and Arthington, 2002). Consequently, despite the mitigation focus being on the longitudinal connectivity of salmon, other ecologically significant flow characteristics that support salmon functioning are not reflected, so species viability could still be undermined. Elsewhere in the literature, there are also examples where trade-offs for valued species can occur through an overreliance on seasonal releases to aid their connectivity, at the cost of a reduction in crucial marginal lateral habitat areas at the fringes of freshwater bodies (Muhlfeld et al., 2011). So in effect, the other river flow building block 'needs' of a species could be undermined, leading to a detrimental outcome.

Previous work has established that the mitigation and environmental controls of schemes from the NoSHEB period are limited in scope, and mostly focussed on aesthetics, and salmon fisheries (Black et al., 2006; Reid et al., 2004; 2005). In addition, however, we have shown here that in the case of the Strathfarrar-Kilmorack scheme, the compensation flows were provided 'solely' to address issues of salmon connectivity and migration. This focus on salmon connectivity is very much indicative of the oversight role of the Fisheries Committee, the surprisingly hands on role of local land owners and stakeholders, and the academic research themes prevalent at the time. Although, with reference to Risbridger (1962), there is evidence that further regard to the river's natural variation of flow was being made as early as 1921, suggesting that there was a more developed understanding of the processes than shown in this case.

Whilst a very narrow scope for regulation, which would not be permissible today (Black et al., 2006), we have also seen that despite the distinct focus on salmon, there could still be detrimental outcomes for the valued species under NoSHEB mitigation. By targeting longitudinal barriers to movement, but mostly neglecting flow regime input changes, both ‘first order’ impacts (Petts, 1987), we have seen that second order changes to habitat, channel form, substrate composition and macrophyte population could still occur, then cause a wider ‘third order’ fish, invertebrate and biotic population response.

5.5.3.3 Post privatisation and the advent of the WFD

The 1943 Hydro-Electric Development (Scotland) Act was repealed as part of the large reworking of the electricity system and its regulatory framework under privatisation in 1989. The introduction of the Environmental Impact Assessment (EIA) framework (85/337/EEC) signified a new wider scope for regulatory control for the UK and Scotland. This new framework mandated that potential impacts of a scheme proposal must be identified and communicated (Reid et al., 2005).

In this era of regulation the role of Europe is key, establishing a common framework of water body classification, objective setting, and monitoring for all individual water bodies across Europe under the Water Framework Directive (2000/60/EC), but also developing a coordinated approach to habitat and species protection through the Habitats Directive (92/43/EEC) in response to the Biodiversity Convention agreed by more than 150 countries at the 1992 Rio Earth Summit. Indeed, European frameworks are seen on both sides of the ‘dual regulation’ system of governance for hydropower present in Scotland, where SEPA deliver on the WFD through the Water Environment (Controlled Activities) (Scotland) (‘CAR’) Regulations 2011, controlling abstraction and impoundment, and Local Planning Authorities or the Scottish Government deliver planning control, implementing elements such as the Habitats Directive (92/43/EEC) and the Birds Directive (2009/147/EC).

5.5.3.3.1 Regulation in a changing world

It is a central theme to this thesis that to deliver sustainable outcomes hydropower regulation must be able to operate in a changing world. Be it due to the potential for a lagged response in downstream conditions (Petts, 1979); the changing perception and prioritisation of impacts (Reid et al., 2004); the uncertainty surrounding climate change and in turn water resource decision making (Werritty, 2002); or the evolving and influential renewables agenda (Ofgem, 2011), there is an inherent temporal aspect that must be considered. Although not within the scope if this research, stakeholder dialogue and the integration of often competing stakeholder needs is also important to this process (Watkin et al., 2012).

Prior to the WFD, the regulatory system lacked the ability to review and revise mitigation and flow agreements (Reid et al., 2004; 2006). It could not, therefore, be very responsive to future change and unable to meet changing needs, leading to environmental inefficiencies and trade-offs. The WFD framework of targets and cycles of river basin planning, however, ensures the domestic regulatory systems are now able to capture more appropriately the temporal elements and change associated with water resource management.

Some similar concerns were reflected through a 2010 European Commission (EC) consultation into the wider functioning, scope and effectiveness of the EIA Directive (EC, 2010). The EIA process was previously criticised for having a temporally limited scope, providing a very static output, so it was suggested that it needed a fixed timeframe for granting development consent, a duration for the validity of the EIA, and monitoring of significant environmental effects of projects post-implementation (EC, 2009). Although the consultation responses on the whole came out somewhat even (<+/- 5%) in respect of supporting or objecting to these proposals (EC, 2011), these proposals on the planning side of regulation reflect a similar appreciation of adaptive management, uncertainty and the precautionary principle seen in relation to environmental flows (e.g. Acreman et al., 2009) and the WFD more widely.

5.5.3.3.2 European led mitigation

In the era of European led environmental frameworks such as the EIA process, WFD and Habitats Regulations, hydropower regulation and mitigation has opened up in scope beyond single species protection to consider water bodies' wider ecological functioning, integrity and value. Indeed, with this international integration and standardisation, whereas the protection of valued species was previously conducted on a local or national basis, with salmon important to local economic and stakeholder priorities, for example, there is now a greater emphasis not only on wider habitats and species, but those of international significance, scarcity and value. This cross border approach to species and habitat protection means that domestic regulation must consider an international context, where fauna of value such as bryophytes or pearl mussels must be protected against a national context and trends such as increasing numbers of small, domestic run-of-river or low head schemes.

5.5.3.3.3 Current mitigation approaches

One of several priorities for current hydropower regulation in Scotland is to deliver valuable national renewable energy with preferably no deterioration to the water environment, or alternatively only when it is justifiable and acceptable. Schemes that make a significant contribution to national renewable energy needs, or where there is a demonstrable wider social or economic benefit, are as a result viewed favourably (Scottish Government, 2010).

As touched upon, abstraction and impoundment activities that may affect Scotland's water environment are regulated and licensed by SEPA under the transposed Water Framework Directive (2000/60/EC), through the Water Environment (Controlled Activities) (Scotland) ('CAR') Regulations

2005. Landscape, habitats and species protection, however, is delivered through the planning consents procedure and the Local Planning Authority for schemes under 50MW, and under Section 36 of the Electricity Act (1989) by the Scottish Government, for those over 50MW (Scottish Government, 2011b). The application of hydropower mitigation in both of these permitting regimes will depend on the scale of a proposal at a site, and the local environmental conditions.

Under the CAR regime flow provisions are now established to provide for some different elements of a water bodies' flow characteristics. Licensing provisions for low, high, and migratory flows are made, in addition to natural flow variability. Provisions for river continuity, and sediment and erosion management are also mandated (SEPA, 2010b). By addressing wider elements of flow characteristics in this way, the mitigation objectives are now in turn orientated towards wider habitat and ecological integrity, albeit with a continued focus on valued migratory species such as salmon and trout where present. It is stated, for example, that setting no abstraction below a hands off flow of Q_{90} is done to prevent drying of the channel and the reduction in wetted width. Maintenance of high flows through an abstraction limit of 1.3 to 1.5 times the average (Q_{30}) flow in the depleted reach, however, maintains the velocities and turbulence necessary to maintain the natural composition of water dependant plants and animals, and physical habitats built around natural erosion and deposition processes (SEPA, 2010b).

The issue of river continuity has also now developed from considering the migratory needs of just salmon, to now also those of trout, eel and lampreys. Intake weirs are screened to protect downstream passage, tailraces are designed and located so as to not attract migratory species, upstream needs are addressed through fish passes designed for species present, and seasonal flows help trigger migration, enabling fish to pass natural obstacles and to progress upstream.

Scottish Natural Heritage (SNH) is a statutory consultee advising on issues of species, habitats and landscape protection, feeding into the determining authority, be it the Local Planning Authority, or the Scottish Government. Their wider conservation role is shaped significantly by European level obligations, such as through the Habitats Regulations, protecting the internationally designated areas such as Special Protection Areas (SPAs) and Special Areas of Conservation (SACs), as well as national designations such as Sites of Special Scientific Interest (SSSIs) and National Scenic Areas (NSAs). The scope of SNH's remit reflects further the consideration of mitigation characteristics applied to hydropower, but also the determination of if a proposal is indeed appropriately designed or located.

For new schemes, consideration is given to impacts on wildlife and habitats, landscape and visual impacts, and impacts on recreation, access and enjoyment. All elements of the scheme proposal are considered including the weir, dam and intake; tunnel or pipeline; and turbine building and tailrace; in addition to issues of construction. Protection for otters, wildcats and bats is established as European Protected Species under the Habitats Directive, whilst also including Atlantic salmon, lamprey, freshwater pearl mussel and water voles for example (SNH, 2010).

This current mitigation approach is very much indicative of the European led regulatory framework, but is of course set against existing infrastructure characteristics and flow legacy, and wider national renewable energy trends. As examined through consideration of the trajectory of the hydropower sector in Scotland elsewhere in this chapter, mitigation of small and micro schemes, and revising the approaches of existing water licenses are shown to be two current regulatory needs.

5.5.4 The development and focus of hydropower mitigation in Norway

Given the fundamental properties and hydrological alteration of hydropower there are similarities in the impacts experienced and mitigation applied in Scotland and Norway. Scheme and national hydropower characteristics, hydrological and ecological baseline conditions, and governance frameworks and stakeholder influence, however, results in different impacts and the resulting application of mitigation may, thus, in fact differ.

Up until the 1991 Norwegian Energy Act that liberalised the energy market, power companies had to supply electricity to a given geographical area. This obligation meant that municipal and regional government had a prominent role in hydropower development, with several municipalities having shares and direct ownership in hydropower companies. Although this meant there were local interests related to the plant and its production, local stakeholders would still undergo economic and social impacts from hydropower construction and operation (Knudsen and Ruud, 2011).

5.5.4.1 Common impacts from hydropower in Norway

Whilst stakeholder concerns will vary by scheme, in rural regions these are dominated by those relating to tourism, outdoor recreation and salmon fishing, and often are intertwined with local economic interests (Knudsen and Ruud, 2011). Having been seen early on as insignificant relative to the benefits, after 1950 there was growing consideration of the impacts from hydropower on scenery and other aspects of the environment. This consideration led to the application of mitigation and limitations on proposals. Consequently, in the 1960s and 1970s there was a wider recognition of the need to optimise design within the environment to improve aesthetic acceptability (Hveding, 1992).

Some of the most common negative effects from hydropower in Norway include the permanent or partial drying of riverbeds, frequent changes in water flow leading to fish stranding, and smolt mortality due to downstream migration through turbines (Hansen et al., 2008). Indeed, these are some of the classic impact characteristics from hydropower, stemming from moderated flow in a depleted reach, a flashy, ‘blocky’ hydrograph, and reduced longitudinal connectivity due to impoundment (e.g. Richter and Thomas, 2007).

In addition to these factors, the prevailing natural resource base and characteristics of hydropower in Norway are also seen to provide more specific outcomes for downstream conditions. Norway is dominated by large storage schemes, which with limited reservoir drawoff points and a peaking operational approach are seen to result in altered downstream water temperature. For example, the Grana power plant on the Orkla River operating with frequent, shorter generation periods in July to September caused downstream water temperature to vary by 6°C from one day to the next (Tvede, 2006). Similarly, other sites with reservoir drawoff from points at significant depth have had a moderating, insulating effect on downstream temperature, where on average sections below the tailrace are 1-5°C lower in midsummer, and 0.5-2°C higher during winter (Johnsen et al., 2011).

Unlike in Scotland, an important consideration for the successful operation and impact mitigation of hydropower in Norway is the interaction with snow and ice in the winter. Beyond the storage characteristics and seasonal precipitation input profile, in-river ice formation can further increase the velocity from hydropower outlets by concentrating flow into smaller areas, raising the erosion potential of river banks and river beds (Tvede, 1993).

This emergence of environmental concerns and the resulting historical application of mitigation reflects use patterns in Norway, with an emphasis on salmon fisheries and outdoor recreation. The prominent role of regional and municipal government also means that these local interests are represented, leading to reparations for losses. With early environmental consideration being limited to salmon as a valued species, however, consideration did not extend to wider habitat and ecological functioning. This was also the case in Scotland, and it was suggested above that this was due in part to there being no interest group or economic pressure for these wider elements, meaning they were neither part of the impact agenda nor of the accompanying debate. There were, however, large scale protests and national political debate around the proposed Alta River scheme in Finnmark, Northern Norway in 1979-81. Rather than focussing on specific aspects of ecology for example, the debate gained momentum as a number of interests groups coalesced representing a raft of issues, including indigenous land rights, the legitimacy of centralised decision making, and a wider debate regarding growth versus conservation (Anderson and Midttun, 1985).

5.5.4.2 Traditional mitigation approaches

Reflecting the continuing role that regional and municipal public authorities have in electricity provision, mitigating impacts through the provision of local financial reparation and payments has long been an established mechanism in Norway. The 1917 Water Course Regulation Act set out a framework for conditions to offer reparations and compensation for damages, commonly as taxes and fees from operators to the municipality where the scheme is located, to serve public interests such as health, education and local employment (Knudsen and Ruud, 2011).

Outside of payments, providing a static minimum flow is one of the oldest mitigation provisions for hydropower impacts in Norway, with often a higher constant value in summer over winter (Alfredsen et al., 2011). Higher water levels on rivers and reservoirs in the summer and early autumn have often also been provided to serve landscape, aesthetic and seasonal outdoor recreational use, such as hunting, fishing and boating (MoPE, 2012).

A consistent concern for Norwegian hydropower has been the impaired upstream migration of Atlantic salmon, and the downstream movement of smolts and kelts through turbines and reservoirs. As a result, traditional mitigation measures for regulated rivers include fish stocking, weirs, fish ladders, and downstream fish-passage facilities (Johnsen et al., 2011). Fry and fingerlings are most commonly stocked in Norway (Fjellheim and Johnsen, 2001), but overall the effectiveness of restocking varies greatly depending on the species, population and environmental conditions (Einum and Fleming, 2001). There are some 344 registered fishways for Atlantic salmon in Norway, serving upstream and downstream migration, with a peak in construction following the significant growth in hydropower from 1960 to 1980. 66% of these concrete pool and weir ladders are passing fish effectively, with the poorest performers often on smaller rivers and higher reaches where they are not monitored and maintained sufficiently (Fjeldstad, 2012). The large number of reservoir storage developments, with inter basin transfer, rather than simple in-river schemes, however, means that there is less need for fish passes of this nature.

Weirs have long accompanied hydropower in Norway. They are very common with over 1000 in the country serving different purposes, such as creating a consistent habitat for fish, maintaining water levels, and to prevent the exposure of rocks for aesthetic and habitat purposes (Johnsen et al., 2011). Whilst basin weirs of this nature do compensate for habitat loss and reduced flow around hydropower infrastructure and abstraction points, they do reduce the water current and flow, which present less suitable habitat conditions for Atlantic salmon, and can create lateral habitat loss and monoculture (Karlström, 1977; Heggenes and Saltveit, 1990).

The massive 2100MW capacity Ulla-Førre hydropower development is an example of a large Norwegian storage system, with significant interbasin transfer and complex tiers of reservoirs and generation stations. As part of this development, the population of Atlantic salmon in the river Suldalslågen was believed to be affected by the new downstream hydrological regime, so from 1974 a minimum flow of 12 m^3/sec in winter and 51 m^3/sec in summer was set, the highest regulated minimum flow in Norway. The river was also stocked with farm salmon to maintain the population, and compensation was paid to the owners of the fishing rights (IEA, 2006). These elements are typical of traditional approaches to hydropower mitigation in the 1960s, with a less targeted approach that only seeks to address directly losses in salmon and general aesthetic elements. This approach is indicative of the significant economies around salmon fishing, and the wider recreational use and appreciation of the water bodies of this kind.

5.5.4.3 Newer mitigation approaches

Hydropower mitigation in Norway has over time become more targeted, with specific methods used to address the particular needs and local characteristics of a water body. For example, where upstream migratory fish are distracted by a hydropower outlet, river bed banking has been used to guide populations upstream, or where spawning habitat loss occurs in regulated rivers, the addition of gravel is used to provide suitable spawning locations for Salmonids (Barlaup et al., 2008).

The same river Suldalslågen section of the wider Ulla-Førre hydropower development considered above has been part of an ongoing trial site, with coordination between Statkraft the generator, local interests, the environmental authorities, the water resources administration and research institutions. Here a series of mitigation measures were applied that are reflective of the development of efforts and findings at the site, but also give insight into the wider progression in the application of hydropower mitigation in Norway. From the late 1980s, rather than simple hatchery restocking that often disrupted salmon life cycles, the mitigation approach shifted to consider the natural processes in the river. For example, to prevent dried out river beds and the stranding of juvenile fish, stipulated limits were made on the speed of flow change, limiting it to under +/- 3% per hour change downstream of Lake Suldalsvatnet. Additionally, from 1998 to 2000 authorities reduced the amount of water in spring and early summer to raise water temperature, and initiated a naturally timed large flood in spring to wash out sediments and algae to help migration. A weekly fluctuating flow in summer between 50-72m^3/sec was also applied to help trigger salmon migration to the river. Then in addition from 2000, smaller floods were applied in spring to initiate smolt migration (IEA, 2006).

The mitigation applied to Suldalslågen is fairly progressive, with the consideration of ecological flow needs to prevent stranding, flush sediments and algae, and trigger migration, that engages with the linkages between flow inputs, habitat characteristics and ecological outcomes. Although a test case of sorts, engaging with local stakeholders, challenging the dominant approach of restocking, and considering salmon lifecycles and ecologically significant flow processes, from the late 1980s is fairly early in the wider improvement trajectory in hydropower mitigation.

5.5.5 Reflecting on mitigation development in Scotland in light of the Norwegian experience

Although sharing an initial mitigation approach of minimum flow, with seasonal variability, weirs, fish ladders, and downstream fish-passage facilities, and to a lesser degree fish stocking, which did not occur in Scotland on the scale found in Norway, there was a shift for Norwegian mitigation to be more focussed on more specific national needs. Indeed, this chapter has argued that whilst there was a similar trajectory of hydropower uptake and development, stemming from an industrial need and maintained government support, the characteristics of hydropower in the two countries diverged in line with national resource characteristics and wider energy policy. To compare mitigation techniques directly in both countries in isolation is therefore less useful, but we can still take value from examining the basis to the debate, the role of stakeholders and how this shaped mitigation outcomes. The section has additionally added to the body of work on the emergence and development of mitigation in Scotland.

It has been shown previously that hydropower mitigation and regulation in Scotland has developed in phases (Reid et al 2004; 2005), with the approach in the pioneering (Reid, 2002) and NoSHEB (Black et al., 2006) periods developing slightly in complexity, but being solely for the benefit of private landowners and salmon fishing interests. There has, however, been uncertainty about the underlying decision making and mitigation goals of NoSHEB (Black et al., 2006), which set against the present legacy and challenges of hydropower in Scotland, presents a gap in knowledge regarding the long term implications of certain approaches, context and specific decisions.

Through the example of the Strathfarrar-Kilmorack scheme this section has highlighted how the overriding theme of longitudinal connectivity has dominated stakeholder dialogue and shaped mitigation approaches. This issue of salmon migration and connectivity, is traced back to the prevalent research agenda at the time, but also is shown to be the 'sole' objective of NoSHEB, and a product of specific fisheries stakeholders who recommended mitigation approaches themselves. It is also shown here that an additional level of flow agreement exists to that seen previously (i.e. Black et al., 2006), showing minimum flow rates in addition to freshet flow rates. These agreements display a slightly more detailed mitigation approach to that explored in previous work.

Although NoSHEB mitigation has been clearly acknowledged as inadequate in comparison with current understanding and regulatory demands (Black et al., 2006), the application of this dominant historical mitigation approach to Petts' (1987) orders of impact framework highlights clearly the types of hydropower impacts being considered. It also shows the effect of the dominant agenda on mitigation approach, and how it differs from a more developed understanding of ways in which flow regimes (and their change) can support (or undermine) aquatic biodiversity (Bunn and Arthington, 2002). Norway has also been shown to display similar historical concerns such as the impact on salmon fisheries and aesthetic elements, and similarly addressed them with minimum flow provisions and fish passes. The history of regional generation, and resulting heightened role of municipal and regional government with a local mandate, however, has facilitated a greater previous reliance on financial compensation and reparation to public funds.

Compensation payments were used in the NoSHEB period, but these were to specific private landowners (NoSHEB, 1969b), rather than serving a wider public interest, and there were no equivalent measures to those found under Norway's 1917 Water Course Regulation Act that established a framework for compensation for damages as taxes. Indeed, no wider regulatory culture exists in the UK and Scotland for compensatory payments, certainly not to the extent or as early as that present in Norway. The only comparable high profile element has come about more recently through the Section 75 of the Town and Country Planning (Scotland) Act 1997, that enables a council to secure contributions to services, infrastructure and amenities in order to facilitate a proposed development.

There is shown to be a similar basis to initial debate regarding fisheries, aesthetics and recreational use in both countries, which in turn led to shared early mitigation approaches in the main. The characteristics of the hydropower resource and installed capacity in Norway, however, have subsequently meant there are different mitigation needs in that country. In addition to mitigation in Norway becoming much more targeted at specific issues, this means that mitigation more commonly addresses the implications from large storage systems, such as downstream temperature changes or speed of flow change.

The timing of this transition in mitigation approach in Norway, away from simple fish stocking, weirs, minimum flow and fish pass facilities, towards targeting temperature, habitat and a range of environmental flow elements, however, appears significant. Specifically, it is much earlier than the wider trend for this through EIA and European habitats and species protection that took place in Scotland. It is possible therefore that mitigation in Norway was more progressive in this respect. This position is perhaps down to the greater role of regional and local public representation in the hydropower industry, which leads to a more collaborative and results-focussed stakeholder landscape, where specific potential impacts and water use needs are better represented.

Privatisation, European regulatory Directives, and more recently the renewables agenda, have brought about a different regulatory and mitigation landscape for Scotland in the last 25 years. The opening up of the scope of regulation to consider wider ecological and habitat functioning has led to a more complex and robust mitigation approach that is able to engage with the risks and trade-offs of hydropower more readily. In light of the renewables agenda, the central theme in debate and regulation is now one of proportionality and balance, where environmental degradation becomes more acceptable if the energy benefits are significant.

As also suggested above with respect to hydropower license reviews, against the framework of Reid et al., (2004;2005) we are now seeing an additional 'phase' in Scottish hydropower regulation, and in turn mitigation, where national energy needs and characteristics play an increasing role. Be it requiring mitigation to respond to energy trends, such as is the case with risk to bryophytes from increasing numbers of small Feed-in Tariff schemes (Demars and Britton, 2011), or changing patterns of storage reservoir use, as demonstrated in Chapter 3 and also considered in Norway (Solvang et al., 2012), an increasing consideration of energy trends and needs is reflected through mitigation.

5.6 SMALL AND MICRO HYDROPOWER REGULATION

With many of the ideal sites having been developed and large impoundment schemes becoming increasingly environmentally unacceptable in both Scotland (DECC, 2011b; Scottish Government, 2011) and Norway (MoPE, 2008), a remaining area for hydropower development is in small and micro generation schemes. Alongside refurbishing existing schemes and reviewing existing licenses under the WFD, the construction of small scale hydropower is a key area of activity in both countries. Due to its historical development and continuing relevance, regulators have significant experience in reconciling the national energy benefits of large hydropower with its local level trade-offs. Although still serving the wider transition to low carbon generation, however, small and micro generation often presents a fairly new and evolving regulatory challenge as its benefits are of a smaller magnitude in energy terms, and may be restricted to local or community level interests. This section will therefore briefly examine the context and regulatory approach taken to small and micro hydropower in Scotland and Norway and consider the implications for sustainable renewable energy from this developing, high profile area.

5.6.1 Scotland

Chapter 4 of this thesis has shown that the 2010 UK Feed-in Tariff (FiTs) mechanism opened up hydropower generation in Scotland to smaller, domestic and community scale schemes, but also presented a new and evolving challenge for regulation. Although open to schemes up to 5MW, the attractive tariff weighting and suitability for this scale of generation mean that the sub 100kW and indeed sub 15kW range represents a vibrant area of growth in Scotland.

Whilst acknowledging the local socio-economic benefits, Scottish Ministers outlined that no individual or accumulative adverse impact would be permissible in sub 100kW schemes due to their reduced contribution to national renewable energy needs (Scottish Government, 2010). This stricter regulatory approach reflects the slightly different regulatory needs. Where previously energy gains are balanced against environmental trade-offs (e.g. Reid et al., 2004), here the scale of development, and wider societal benefit, cannot justify environmental losses.

The regulation of hydropower schemes in Scotland under 100kW (approx. <0.35GWh/yr) utilises a checklist to guide developers as to the suitability of proposals, to streamline the licensing process under the Water Environment (Controlled Activities) (Scotland) ('CAR') Regulations 2011, and to reduce the regulatory burden. It is through this SEPA (2010b) guidance document that we can see the regulatory approach and elements under consideration for this scale of hydropower development.

Firstly, proposals are deemed most suitable if sited in degraded parts of the water environment that are not scheduled to be improved under the RBMP process. Secondly, where this is not the case, proposals in small, steep sided rivers or streams are preferential, as cascading reaches and deep pools are often unsuitable for migratory fish and present natural barriers, and display little variation in wetted width. Thirdly in turn, schemes are provisionally acceptable if they deliver net benefits to the ecology of the water environment. Finally, a range of other elements are viewed positively, such as utilising flow from an existing weir or outfall, being located on a minor tributary (<10km^2 catchment), having a very short depleted reach (<500 metres), and abstracting without causing a breach in river flow standards, which for 'good' is typically around 20% of average summer flows, 30% of average winter flows and 40% of spate flows (SEPA, 2010b).

As statutory lead on habitat, species and landscape issues, Scottish Natural Heritage also feed into determinations on this scale of hydropower generation. Of course supportive of the Scottish Government's targets to address climate change, and mindful of the economic benefits of renewable energy, SNH seek to support the development of hydroelectric schemes in appropriate locations and with suitable design and mitigation. Casework and resources are prioritised based on risk, given site conditions and scheme characteristics (SNH, 2011), with consideration given to visual aspects of infrastructure and construction, pollution risk from construction, flow change and variability, and impacts on habitats and valued species (SNH, 2010).

5.6.2 Norway

Due to the wider trend for very large storage schemes in Norway, small hydropower is categorised as being under 10MW, allowing for an appreciable amount of diversity in scheme type, characteristics, and resulting ecological implications. Mini hydropower is between 100kW and 1MW, and micro schemes are those under 100kW.

There is a lower level of scrutiny for the development of small hydropower in Norway, with fewer regulatory licenses required than larger proposals, and only falling under the Norwegian Water Resources and Energy Directorate (NVE), and Water Resources Act, rather than the Ministry of Petroleum and Energy (MoPE) also. Indeed, whereas larger proposals are subject to the 1984 Norwegian Master Plan that created a national spatial system for environmental protection and hydropower resource availability, this does not extend to small scale hydropower. In addition, specific valued watercourses are protected in Norway from hydropower development under four Protection Plans, adopted by Parliament between 1973 and 2009. Schemes under 1MW, however, known as micro and mini hydropower respectively, are exempt from this restriction. Indeed, at this scale of development, licensing is delegated to the County Council but is based on a recommendation from the NVE (Knudsen and Ruud, 2011). Instead, County plans are being developed, to be centrally approved by the Ministry of Environment (MoE), that guide small scale development to suitable areas using criteria and guidance from MoE. In collaboration with stakeholder and regulatory bodies, Counties were instructed to develop county spatial plans for small hydropower plants, ensuring that no biodiversity, recreation or large landscape values are lost. The aim was to provide a comprehensive assessment tool that enabled the licensing process to be more transparent, efficient and consistent, for government, developers and wider society. It was felt a common methodology in all counties would increase the collective value of the plans by enabling comparisons and consistency across regions, enabling greater efficiency in development and supporting better site selection (MoE, 2007).

In these plans, each theme of protection normally has a three part sensitivity scale, overlaid spatially, and conveyed through subsite summarising text, with guidance as to how these important environmental interests and values should be addressed in the individual projects within the region. MoE set out that the plans should give consideration to a variety of issues including, valuable landscape and mountain areas, fjords, biodiversity, undeveloped natural areas, fisheries, culture and heritage, and outdoor recreation. Taking the example of fish protection, high value areas are national salmon rivers and those that support priority trout populations and large fishing interests, medium value areas are those that support some migratory fish populations but without the significant interests and economies, and low value area have neither valued fish populations, or fish interests (MoE, 2007).

5.6.3 The potential for a differing approach

As the potential for further large schemes diminishes in Scotland and Norway, both countries are experiencing a shared pressure for the uptake of small and micro hydropower proposals. Here we see that in comparison to large schemes, regulation at this scale of development is increasingly delivered at a local level. In Scotland, determination has shifted to local planning authorities and to ensuring that local knowledge is applied to decision making (Scottish Government, 2011b), although many developers report a CAR licence is more difficult to obtain than planning consent (Black, A., 2013, pers. comm.) In Norway, the emphasis is on developing regional spatial assessment tools.

The level of scrutiny outlined above appears to differ, however, with Scottish water regulation through SEPA applying a stricter regulatory approach, not allowing any environmental losses, whereas Norway applies exemptions to spatial restrictions and reduced licensing demands for this scale of development. It is perhaps unclear, however, if Norway is taking a lighter approach with small hydropower proposals due to their relative impacts when compared with large schemes, and vast resource availability, or alternatively if it is a move to reduce regulatory burden and costs where the risk is lower. It should be noted again, as set out in analysis within Chapter 5 above, that both countries have developed a similar percentage of potential technically and financially viable national hydropower capacity, with Norway 57% and Scotland 54%. Therefore, arguably as both countries are at a similar stage of potential resource development, differences in regulatory approach are due to differing wider regulatory objectives and context.

What is clear from this brief overview is that Norway, mirroring its approach taken for large schemes, utilises a greater level of strategic and spatial planning to support regulatory and industry decision making, and site selection. Although the WFD has brought in more integrated decision making through river basin planning, and there are examples of the application of spatial guidance in the national parks in Scotland (i.e. LLTNP, 2012), and in their species and conservation advisory role SNH have developed spatial screening for internationally designated sites, Scotland does appear behind Norway in developing and applying strategic spatial tools for hydropower development. Given that small hydropower is often proposed and developed on a site by site basis, rather than as part of a wider development programme, and that there are increased risks from cumulative impacts to the environment, spatially guided planning would appear to have an important role in hydropower regulation. Dating back to the early 1980s with the 'Samla' Master Plan, Norway has an increased use of strategic spatial mapping to inform regulatory decision making. This difference is potentially due to the heightened role hydropower has in Norway in terms of energy policy and also stakeholder awareness, but also because it supports the fairly significant role of regional and municipal governments in the regulatory process.

5.7 CONSIDERING THE RESULTS TOGETHER

To inform the wider challenge of delivering sustainable renewable energy in a changing world, this thesis examines how the historical emergence and continuing changing wider context for hydropower in Scotland has shaped its characteristics and in turn resulting implications for sustainability. This chapter uses Norway as a comparative example to further inform understanding on specific high profile areas of policy and regulation, reflecting these overall research objectives, and innovatively looking to identify the linkages and creating dialogue between disciplines and scales. It has been demonstrated here that Scotland and Norway share many contextual elements that in turn lead to similar outcomes or challenges. For example, in both countries hydropower emerged from an initial industrial energy need, underwent a development period under a central public body, had a similar basis to objection and debate, has since reached a similar point in development, and is now focussed on the growth of small hydropower development and license renewal. Conversely, there is also a fair amount of divergence between the two countries stemming from topographical characteristics, national energy needs, profile of precipitation input, and the role of regional and municipal government. In the case of Norway especially, this has led to different dominant scheme characteristics, resulting environmental challenges and regulatory constraints. It is also demonstrated here acutely, however, that it is often the interaction of multiple contextual elements that contribute to specific pressures on regulation and measures to obtain environmental targets. For example, due to the development profile of electricity generation in Norway, there is a national reliance on hydropower capacity, which in turn puts pressure on regulatory efforts to make environmental improvements to schemes. This difficulty is compounded further, however, by a seasonal runoff profile that is divergent from demand needs, making specifically storage capacity even more crucial to national energy security.

Table 5.4 presents a summary of how these crucial contextual elements identified in this chapter influence sectoral characteristics and in turn shape regulatory outcomes and pressures. By presenting visually the avenues by which national characteristics, such as a dominant runoff profiles or historical regulatory development, can influence scheme level decision making regarding environmental changes or prevalence of strategic spatial tools for example, the mechanism for connectivity between disciplines and scales is highlighted. Here we see contextual elements fall into four main groups, those being;

- **Natural resource characteristics** - e.g. topography and runoff profile
- **Stage of resource development** - shown here is fairly similar for Scotland and Norway

- **Regulatory history and role of regional agencies** - seen to create a slightly different regulatory approach and framework
- **Wider energy needs and policy** - placing hydropower within the broader energy agenda

Having identified these contextual groups, the mechanism by which they can influence sustainability outcomes, and the significance of the way they can interact, we arrive at a point where we have a better understanding of the factors and interactions that need to be navigated in order to support sustainable decision making. This increased understanding of cross disciplinary and multi scale connectivity can also be applied to other countries, scenarios and technologies, to help deliver sustainable renewable energy.

This outcome is also of direct relevance to international regulatory development such as the WFD, which often seeks to obtain cross border consistency and standardisation in the approach and design of regulatory frameworks. The example here shows clearly that there must be capacity in international frameworks of this nature to allow for specific national characteristics, conditions and objectives as, through the mechanisms identified here, they are very influential in shaping sustainability challenges.

Table 5.4: A summary of how contextual elements shape regulatory outcomes for Scotland (blue) and Norway (red)

CONTEXTUAL ELEMENTS	NATIONAL CHARACTERISTICS	SECTORAL OUTCOME	REGULATORY OUTCOME
Topographic characteristics	Diversity in landscape	Associated diversity in scheme type, smaller scheme average	Reduced occurrence of dominant impact characteristics
	50% of Europe's hydropower reservoir storage capacity	Dominance of reservoir storage schemes, serving precipitation profile	Greater energy reliance on reservoir schemes. Associated impact
Precipitation input profile	Less seasonality, comparatively	Reduced need for seasonal storage	More flexibility in scheme operation
	Significant spring upland snow melt input	Seasonal and interannual storage is key for national energy security	Heightened pressure on licence reviews and revising operation
Stage of resource development	Scotland 54%	Shift away from the construction of further large impoundment schemes	Shared focus on small and micro development, revising licences and refurbish existing schemes
	Norway 57%		
Regulatory development	1943 (NoSHEB) Act; 1989 privatisation; 1999 devolution; 2000 WFD; 2002 RO	Multiple changes in water regulation, and influential energy policy	Challenging and evolving regulatory framework
	1917 Watercourse Regulation Act; 1921 NVE; 2000 WFD	Continuity of longstanding principles of public ownership, local renumeration and local level governance	Governance continuity and consistency in regulatory approach
Role of regional and municipal government	Privatised sector. Increasing regulatory role for local planning authorities	Less single strategic approach. Only recently increasing regulatory capacity of local authorities	Often case by case basis. Regional strategic and spatial tools starting to emerge since WFD
	Long history of regional and municipal government ownership and involvement	Experience and mechanisms to build in local level expertise and outcomes into decisions	Mitigation more readily reflect local concerns. Greater use of spatial planning and strategic tools, since mid 1980s
National role of hydropower and wider energy needs	Complementary role alongside diverse wider portfolio	As rise in output of other renewable technologies occurs, reduced single reliance on hydropower contribution	Reduced regulatory pressure, allows environmental gains to be made at small capacity loss
	Single reliance on hydropower, and significant increase in winter demand	Maintained capacity and seasonal output are crucial for national energy security	Significant pressure to prevent hydropower losses

CHAPTER SIX: DISCUSSION

With an enviable ecological, landscape and hydrological resource base, Scotland as a "hydro nation" (Scottish Government, 2012b) has a long history of river flow utilisation and regulation to serve a range of societal needs. The resulting emergence and development of hydropower has occurred against a changing wider energy and governance context, which has shaped its characteristics and implications for sustainability.

Hydropower regulation must now support the delivery of high profile binding EU renewable energy targets, whilst also meeting obligations to protect and improve the ecological status of water bodies. Yet as Scotland orientates itself as a leader in Europe on climate change, transitioning to increasing amounts of renewable generation across a handful of technologies, and moves to greater energy and political autonomy, there is little policy harmonisation (OECD, 2011) and little appreciation and knowledge regarding the connectivity and role this wider context plays in shaping outcomes. This position has arisen despite the acknowledged potential for water policy trade-offs from energy objectives (Volkery et al., 2011).

This thesis therefore takes a set of complementary approaches to examine critically the effect of a changing wider energy and policy context on hydropower sustainability in Scotland. By identifying these linkages and creating dialogue between disciplines and scales, this thesis seeks to inform the pursuit of sustainable renewable energy through policy and regulation integration (e.g. Bührs, 2009).

The wider research base reflects on the natural flow paradigm of rivers (Poff et al., 1997; Richter et al., 2003), how this supports aquatic biodiversity (Bunn and Arthington, 2002), and that a change in flow variability leads to a downstream shift away from equilibrium (Leopold and Maddock, 1953) and often a loss of ecological diversity and integrity (Petts, 1979). As a consequence of this understanding, the trade-offs and implications from hydropower are shaped by local hydrological conditions (e.g. Gilvear et al., 2001; Marsh and Anderson, 2001), but, crucially for this study, also scheme design and operational characteristics (Petts, 1984).

Understanding how the wider changing policy and energy context can shape design and operational characteristics is therefore crucial for sustainable renewable energy, and supporting policy integration (Bührs, 2009). Previous research in Scotland has shown that hydropower mitigation and regulation there has developed in phases (Reid et al 2004; 2005), with evolving types of environmental flow provision arising from slowly developing regulatory scrutiny (Black et al., 2006). Research in Norway is starting to raise questions (Knudsen and Ruud, 2011) and examine what the water resource implications are of a renewables led, changing energy need profile (Wolfgang et al., 2009; Solvang et al., 2012). In addition, interdisciplinary approaches are being encouraged (Richter et al., 2006) and research is emerging that seeks to obtain environmental improvements, whilst engaging with aspects of water resource use (Bruno and Siviglia, 2012).

Yet, there is little other widely communicated understanding of the interdisciplinary interaction and connectivity between the changing energy agenda and policies, and water and environmental outcomes from hydropower. This evolving situation presents a distinct gap in knowledge. Further understanding of this dynamic is of value to stakeholders operating at an international, national or local level, in energy, environment and the wider sustainability field, in policy, regulation, industry and academia. This gap in knowledge is ultimately an obstacle (e.g. Bührs, 2009) to the pursuit of environmental integration and increased sustainability of hydropower.

This thesis takes a longitudinal and interdisciplinary approach, drawing on an examination of water and energy policy and regulatory frameworks, national hydropower and energy mix characteristics, reservoir hydrological data, and archival sources. There are three case studies, chosen for their ability to provide insight through different aspects and scales of this dynamic, namely; the interaction of national generation trends and outcomes at a specific hydropower scheme; the role of incentive policy measures in shaping hydropower; and, a comparative examination of the context and resulting trajectory of hydropower in Scotland and Norway.

This discussion will consider each of the three research chapters (chapters 3, 4 and 5) in turn, before examining them together, to engage in overall themes and the contribution from this research.

6.1 CHAPTER THREE: CRUACHAN AND A CHANGING WIDER ENERGY MIX

Under a high profile climate agenda, as Scotland and the UK transition to an ever increasing proportion of generation from renewable technologies (National Grid, 2011), understanding the implications for the grid integrity (Ofgem, 2013b) and feedback for the operation of grid balancing elements (Deane et al., 2010) is central to challenges of energy security and stability. In turn, as hydropower generation patterns shape water management outcomes (Petts, 1984), engaging with, and communicating how, this trend can affect reservoir and ecological outcomes at Cruachan pumped-storage scheme is important for integrated decision making and sustainable renewable energy.

Chapter three has demonstrated that the changing national energy mix, and specifically the penetration of increasing amounts of wind generation can result in a shift in operational profile and reservoir variability at a flexible pumped-storage scheme. This finding is of additional significance, as it adds further insight to a small but growing field of research that seeks to connect wider grid trends with hydropower operation and outcomes.

Indeed, by demonstrating that hydropower operation and reservoir management can be influenced by a change to traditional energy structures and composition, this central finding provides an example to confirm the suggestion by Knudsen and Ruud (2011) to this effect. Demonstrating the influence of a transition in the wider energy sector, here towards greater renewable provision, is similar in effect to that identified by Wolfgang et al. (2009), where deregulation of the national energy market in Norway altered the demand profile, resulting in a response in the operation and in turn reservoir management of storage hydropower schemes.

One similar recent international high profile development related to increasing contribution from renewables and the effect on hydropower and its sustainability, is the potential for Norway to take on additional balancing load as part of the so called 'battery for Europe' agenda. Up till now research in this area has focussed on its potential (Solvang et al., 2012) and possible energy outcomes (Graabak and Skelbred, 2012). Research funding proposals have recently been submitted to examine the significant uncertainties regarding outcomes for habitat, stakeholder and regulatory aspects, and as such if Norway will be taking on an overly large ecological burden on behalf of Europe (J Sauterleute 2013, pers. comm., 7 May). In light of this emerging research question, the study and outcomes shown with relation to Cruachan are timely, and even slightly ahead of what could be a significant and high profile body of work that considers how hydropower is responding to changing energy demands relating to increased renewable generation, and engaging with any resulting environmental and regulatory implications

With the need to integrate increasing amounts of other renewable technologies into the UK grid (IEA, 2005), there has been a renewed consideration of pumped storage hydropower in Scotland (Scottish Government, 2010b), resulting in the Coire Glas (600MW) scheme proposal.

Having developed guidance on run-of river schemes, SEPA are developing new guidance on storage schemes, expected in 2013, which will give further consideration to changes in loch level allowing assessments of changing riparian conditions (J. Mackay 2012, pers. comm., 15 August). Against this energy context, the outcomes presented for Cruachan offer direct relevance to SEPA as they develop their position and guide industry through sustainability challenges in a changing world. Although hydropower reservoir variability is restricted through water use licenses under The Water Environment (Controlled Activities) (Scotland) ('CAR') Regulations 2011, this example of Cruachan innovatively demonstrates that such regulatory guidance reflects that a wider energy context can shape hydropower reservoir outcomes and trends.

By examining the effect of the changing wider energy context on Cruachan operation, this research sought to identify how this would affect reservoir variability, but crucially also relate this to ecological outcomes through ecologically significant parameters.

To overcome uncertainties regarding the position of thresholds in reservoir variability, that would vary with hydrological and climatic conditions by site (Gilvear et al., 2001; Marsh and Anderson, 2001), this research looked to identify trends in ecologically significant parameters (Bragg et al., 2003), but also identify the direction of change or 'categorical response' (e.g. increase or decrease) (i.e. King et al., 2008) against a small number of standardised reservoir benchmarks taken from Smith et al. (1987).

This study found that against these benchmarks, albeit with some uncertainty through some gaps in the data that will be discussed below, conditions are becoming more viable for macrophytes, invertebrates and fish as conditions move *towards* the ecological benchmarks identified by Smith et al. (1987). This finding also shows that the magnitude and frequency of water level change are becoming moderated, and improving over previous findings at Cruachan (i.e. Smith et al., 1987; Smith, 1980), with this trend accentuated in the summer, presenting further ecological benefits by coinciding with a period of heighted biological significance.

This direction of change suggests that there is a positive synergy with the new operational regime; that of shorter, low magnitude generation resulting from balancing increased renewable generation, and the ecological functioning and integrity of Cruachan reservoir itself. This presents a win-win outcome for delivering the renewable balancing benefit of pumped storage alongside the ecological and biodiversity goals of managing the freshwater environment. Indeed, whereas this research is founded on the premise of interaction and potential for trade-offs between energy and water policy areas (e.g. Volkery et al., 2011) this is an example of a synergy, where a shift in the wider energy context is positive for water regulation.

A question arises as to whether the change to traditional energy structures and composition, first raised by Knudsen and Ruud (2011), here pursued in terms of renewable penetration, will see a similar response in generation approach and thus reservoir handling at other peaking, load-following storage schemes in Scotland. Certainly this is a potential area for future research, but with this Cruachan case study pursued in part because it is a 'closed system', insulted from other trends such as in natural hydrological input, it may well be the case. Indeed, whereas Smith et al. (1987) conducted a review into reservoir handling and variability in Scotland, given the advent of flexible hydropower as a tool for integrating renewables, such historical literature may in effect be out of date.

As discussed above, chapter three on Cruachan makes a strong contribution to the emerging field of research, emerging out of Norway that considers the outcomes for hydropower from the transition to increasing amounts of renewables, and the wider 'battery for Europe' agenda.

By delivering on the aims of this thesis and providing linkages and dialogues between scales and disciplines, this research delivers an innovative platform and example that brings energy and water fields of study together. By demonstrating the connectivity between these disciplines and scales, and the significance of wider trends for hydropower, this research helps to create a discussion between disciplines that can consider influential trends and their outcomes to serve sustainable renewable energy challenges. Indeed, by identifying the potential for a synergy between renewable balancing and littoral functioning, over existing conditions, this research makes the case that positive win-win outcomes are possible, and that often conflicting goals can be reconciled.

Through this review of reservoir variability at Cruachan, chapter three in part updates the findings of Smith et al. (1987) who provided an overview of Scottish loch water level variability and littoral conditions. It is, therefore, useful in the wider living with environmental change agenda, where research seeks to support sustainable resource management in a changing world. By engaging with the uncertainty regarding the influence of cross-disciplinary issues, it serves to inform the wider understanding and response of environmental integration both in policy and in practice (e.g. Bührs, 2009).

It also provides a further successful example where a building block methodology (BBM) (King et al., 2008) is used to examine and express changes of ecological significance in a fresh water environment, to overcome the uncertainty often associated with pinpointing specific ecological outcomes from water level (or river flow) regime change (Werritty 2002; Arthington et al., 2006; Acreman et al., 2009).

This study of Cruachan, and indeed the wider thesis, aligns well with Richter et al. (2006) who advocate interdisciplinary, science-based approaches to research engaging with aspects of resource use and ecological improvements in the freshwater environment. Furthermore, whereas Alfredsen et al. (2011) and Carolli et al. (2011) contribute to a field that as such engages with aspects of use, this consideration of Cruachan goes further by including consideration of a wider, ‘external’ context that shapes the characteristics and trends of use. As a result, chapter three provides a clear argument for research to not only engage and balance interdisciplinary aspects of use, be it specific hydropower scheme operation or drinking water reservoir storage, but to extend this scope to wider influential policies and trends to support much more sustainable, integrated water resource management.

There is a fair degree of consideration in the energy policy arena towards the implications of the increasing contribution from renewables. This is seen in relation to meeting short term demand (Ofgem, 2013b), the role of storage (Scottish Government, 2010b), and the potential for international balancing (Solvang et al., 2012), for example. Although more widely energy regulation can extend to sustainability issues, such as is the case with biofuel reporting (Ofgem, 2012b), in terms of this trend for increased renewables uptake there is no push to consider potential sustainability feedbacks, such as that presented here in relation to hydropower and Cruachan. In this context, chapter three therefore presents an interesting new element, and highlights a fair amount of policy uncertainty regarding the implications and sustainability feedbacks from this energy transition. It is as such envisaged that further policy work could be undertaken that identifies and highlights other feedback and sustainability implications, positive or negative, across all environmental media, so that the implications of continuing on a path of low-carbon and renewable generation can be fully understood, and reflected through policy.

Water regulation in Scotland must deliver on the energy benefits of hydropower, whilst minimising the trade-offs for the environment (Reid et al., 2004). As explored in this thesis, however, the landscape and challenge for regulation is often influenced by the wider renewables agenda, leading to a response by regulation. This balancing of value is central to the hydro nation agenda (Scottish Government, 2012b).

Whereas the advent of domestic small and micro schemes has appeared on the regulatory agenda in Scotland (SEPA, 2010b) and resulted in related commissioned research (Demars and Britton, 2011), there has not been an equivalent acknowledgement regarding changes in reservoir handling at flexible storage schemes. This may mean that the issue is unknown to regulators, or is considered low risk as it would be picked up by water use licenses. Nevertheless, with the recent proposal for the Coire Glas (600MW) pumped storage scheme, and renewed consideration of storage hydropower in Scotland (Scottish Government, 2010b), SEPA as water regulator will be fully aware of the shift in focus towards balancing schemes, and the associated regulatory implications. The outcome provided by chapter three, that the changing energy mix towards renewables can influence hydropower reservoir handling away from traditional approaches, is a simple message that fits in with this wider energy trend and it is argued here should be reflected in the resulting regulatory agenda.

Chapter three provides a timely and innovative examination of the outcomes and feedbacks from continuing trends in renewable generation uptake, in the context of high profile energy and water policy frameworks. In addition, this research outcome is of increased significance as Scotland continues to take a position of leadership in Europe on renewables, but also seeks to realise, protect and deliver on the high value of the changing water environment sector as part of a 'Hydro Nation' agenda (Scottish Government, 2012b). Indeed, in light of these findings, this policy context, and wider uncertainty around climate change and water resource decision making (Werritty, 2002), it is proposed here that there is a need for a high level national discussion on the role and challenges for reservoirs in Scotland. These parallel yet interlinked policy objectives, in addition to the findings from chapter three on Cruachan, highlights that there is a fair degree of uncertainty about how Scotland wants to use its reservoirs in the future, what changes and pressures are occurring, and what damages are acceptable to deliver societal goals.

Similar to how the NEA (2011) undertook an audit of environmental media, to place a value on the natural environment so as to aid integrative decision making, a central discussion and resulting central plan could help inform sustainable use of Scotland's reservoirs in a changing, resource constrained world.

Chapter three and the wider thesis set out to identify linkages and create a dialogue between energy and water domains to bolster the understanding of policy interactions, trade-offs and challenges, against the context of changing energy needs for a sustainable low-carbon society. The reservoir data obtained provided an opportunity to interrogate water level, and in turn generational variability and profile at Cruachan.

The data limitations have been discussed previously in chapter three. There it is contended that whilst some of the data from 2001-2007 is incomplete, leading to some noise and uncertainty in the data, meaning care should be taken with the conclusions from the research, it is clear that an energy transition at Cruachan has occurred due to differing grid needs under a renewables agenda. It is for this reason, and due to there being similar examples found elsewhere (e.g. Wolfgang et al., 2009; Knudsen and Ruud, 2011), that this research is sufficiently robust for some meaningful conclusions to be drawn from it.

6.2 CHAPTER FOUR: RENEWABLE ENERGY INCENTIVES AND HYDROPOWER OUTCOMES

Whereas the majority of current hydropower capacity in Scotland was established in the mid-20th century (Payne, 1988), expansion in the last 25 years has been under the high profile renewables agenda. To deliver on renewable energy policy objectives, UK government has established a series of evolving financial incentive mechanisms with a range of objectives, support instruments and eligibility criteria.

Whilst open to a handful of technologies, it is proposed here that these incentive mechanisms play a role in shaping the characteristics of hydropower in Scotland, at a scheme and national level. With the implications from hydropower commonly understood to be influenced by local hydrological conditions (e.g. Gilvear et al., 2001; Marsh and Anderson, 2001), and importantly scheme design and operational characteristics (Petts, 1984), however, this thesis also proposes that these energy policy delivery mechanisms can in turn influence the sustainability outcomes and water regulation challenges from hydropower.

Chapter four demonstrates that whilst they are important in shaping the characteristics and sustainability implications of hydropower, incentives do not exist in isolation but are one of many influential factors external to hydropower regulation. Nevertheless, this investigation has identified six *outcomes* for hydropower sustainability in Scotland stemming from incentive mechanisms, including strategic challenges, the potential for the disruption of environmental efficiency, but also some positive synergies with water regulation.

Although it was necessary to unpick the influence of incentives from external policy factors, three key *avenues* for influence have also been identified that contribute to shaping these sustainability outcomes for hydropower, namely; eligibility criteria; financial reward framework; and, the timing of the mechanism. By linking these energy development mechanisms with outcomes for hydropower, this chapter has provided an innovative examination of how the measures have emerged and evolved in relation to hydropower, and indeed how specific elements can shape sustainability challenges and the delivery of water policy objectives and regulation.

Whilst it is widely known that energy policy can influence the successful delivery of water policy objectives (Volkery et al., 2011), this research has provided an in depth account, innovatively demonstrating the mechanisms by which this can occur, highlighting the connectivity between scales and disciplines, to inform integrated decision making (e.g. Bührs, 2009).

The emergence and development of renewable energy policy in the UK has led to an associated body of research literature, for example looking at its early progression (Mitchell, 1995; Connor, 2003), aspects of investment and innovation (Foxon et al., 2005), and most commonly the characteristics and effectiveness of the 2002 Renewables Obligation (RO) (e.g. Mitchel and Connor, 2004; Mitchell et al., 2006; Wood and Dow, 2011). Whilst Harrison (2005) has previously examined the structure of the RO and the resulting deployment of hydropower in the UK, chapter four adds an additional dimension by considering outcomes for hydropower in Scotland not only under the RO, but also the Scottish Renewables Obligation (SRO), and more recent Feed-in Tariffs (FiTs).

The main focus of this literature base is the mechanisms themselves and their ability to deliver on national energy policy objectives and large scale renewable deployment, and consequently does not extend to considerations of sustainability. Chapter four of this thesis makes an additional valuable contribution therefore as it goes one step further in considering outcomes for water regulation and sustainability in Scotland. Indeed, although references to the renewables agenda are fairly common place, and its influence is expected in many areas of policy and regulation (Volkery et al, 2011), chapter four provides additional value as through the example of incentives and hydropower it displays the linkages and mechanisms by which this can occur.

Previous research into the historical emergence of hydropower in Scotland has outlined that this has been accompanied by phases of development in the scope of hydropower regulation and mitigation driven by changes in governance context, stakeholder influence, and scientific understanding (Reid et al., 2004; 2005). The findings of this research chapter into incentives suggests that there is now an additional phase of hydropower governance under the renewables agenda, such is the influence of the wider energy policy framework including incentives.

By linking these incentive mechanisms with regulatory and sustainability challenges, this study of incentives brings together energy and environmental disciplines and bodies of research, and provides a common basis by which to consider and inform sustainable renewable energy now and into the future.

In terms of implications for policy, practice and regulation, chapter four clearly highlights the parallel emergence and development of energy policy mechanisms alongside the current governance framework for water, habitats and species in Scotland. The presentation of this trend is significant as it contextualises the evolving governance and sustainability challenges for hydropower in Scotland, and highlights the existence and basis to areas of conflict, and indeed examples of synergy between energy and environment regimes. This is an important step in informing the pursuit of environmental integration (Bührs, 2009).

It has been demonstrated in this thesis that hydropower regulation in Scotland has had to be very responsive and flexible to this changing energy context, resulting, for example, in related research (Demars and Britton, 2011) and guidance (SEPA, 2010b). Whilst there has been reference to the demands of renewables policy on regulation (Scottish Government, 2010), it is not something that is, or perhaps can be, articulated fully by regulators, and so remains anecdotal knowledge. By identifying and communicating the three avenues through which incentives can be influential (eligibility, financial reward framework, and timing) this research is valuable as it could inform moves for improved policy integration, something that is currently lacking between energy and environment frameworks (OECD, 2011).

An aspiration for the application of these findings is that with this information, water and environmental regulation could be able to engage in the early stages of policy development of energy mechanisms, to minimise unforeseen outcomes and provide more integrated decision making. At a policy planning level, processes for dialogue and co-operation between the different competent authorities, organisations and stakeholders supports better integration and delivery of hydromorphology (Water Directors, 2006). For example, with this knowledge, through the early development of FiTs it would have become apparent that there was no centralised plan or strategic element to the development of hydropower and renewable schemes, therefore either this could have been built in, or spatial and strategic capacity could have been developed in regulation. Similarly, with eligibility for support under the RO including schemes renewed after 1990 under 20MW, greater prior regulatory involvement could perhaps have led to greater advantages being made of the synergies with license revision and environmental improvements.

As is discussed in Chapter 4, the shape and characteristics of incentive mechanisms themselves are continuing to evolve, which it is argued here will again have different outcomes for hydropower. The removal of the RO after 2017, and transition to the new framework involving FiTs with Contracts for Difference (CfD) under the 2013 Electricity Market Review presents an opportunity to apply the findings and thinking presented in this research to the next generation of incentive measures. As further details for CfD are announced this is an opportunity for a further area of research, but also an application of these findings so as to inform the regulatory integration, or if necessary response, of the emerging framework.

Through engaging with hydropower stakeholders at SSE and NPower as part of this research, it soon became apparent that incentive mechanisms do not occur in isolation, but are part of a fleet of elements that feed into decision making, including site environmental sensitivity, resource potential and grid connectivity. This presents a limitation as to consider the influence of incentives is therefore somewhat artificial as other factors also feed into shaping hydropower characteristics and regulatory outcomes.

Nevertheless, this research has therefore endeavoured to identify the specific characteristics and influence of incentives themselves, whilst also considering this wider context. For example, following the advent of FiTs there was a focus on domestic and community scale generation which it is shown here has led to associated spatial and strategic regulatory challenges. However, the influence of FiTs here is only one factor alongside site availability and environmental considerations that has led to smaller schemes becoming more prevalent (e.g. AEA, 2010; DECC, 2011b; Scottish Government, 2011).

One key element of understanding that underpins this thesis is that generation patterns can shape water management outcomes (Petts, 1984). For example therefore, with price for electricity under the RO fluctuating with market value, whereas under the SRO it was fixed under a contract, it was hypothesised in chapter four that RO schemes would seek to profit maximise by targeting peak demand periods. In turn therefore they would display an unnatural, ‘blocky’ release profile and resulting downstream ecological implications. The RO mechanism again, however, does not occur in isolation, so RO schemes would not necessarily be storage and peaking schemes due to the above preference for run-of-river schemes. Nevertheless, it is felt that this approach of considering how specific energy policy elements could affect scheme operation still offers a valuable mechanism to link energy and environmental policy areas, opening up the potential for future integration and dialogue.

One area that chapter four was not able to pursue due to commercial sensitivities, was how incentives shape economic or financial aspects of schemes themselves, and in turn if this leads to specific environmental outcomes. With incentives modifying the financial viability and profitability of schemes, which is of course a pivotal aspect of potential schemes, this presents an opportunity for an in depth study looking at how this shapes sustainability outcomes. Indeed, with ecosystem services and the value of water resources being an increasing tool for decision making (NEA, 2011) and underpinning the Hydro Nation agenda (Scottish Government, 2012b), and this current research suggesting incentives can disrupt the environmental efficiency of schemes, which now maximise income rather than maximising generation, there is uncertainty in this area which research of this kind could inform.

Although there have been almost 25 years of renewable incentives in the UK, it is still an evolving and high profile area of energy policy that remains central to the delivery of binding renewable energy targets. With habitat, species and natural environment protection across all media a high priority in Scotland, addressing uncertainty as to how incentives have shaped sustainability and environmental outcomes for all renewable technologies supported under incentives is of importance. This is especially so for technologies that have large future uptake potential, or which are more contentious. The potential for cross-border comparisons is also significant, as other countries - such as Norway - embarking on a path of incentives, can learn from the significant experience in the UK.

6.3 CHAPTER FIVE: HYDROPOWER TRAJECTORY IN SCOTLAND AND NORWAY

The historical emergence of hydropower in Scotland, and continuing changes in its wider context, have shown to be significant in shaping its environmental and sustainability outcomes. A comparison with the experience and outcome in Norway provides a timely opportunity to examine this dynamic further, whilst also pursuing discussion of some specific shared regulatory elements.

Chapter five has demonstrated that Scotland and Norway share many contextual elements that in turn lead to similar outcomes or challenges. For example, in both countries hydropower emerged from an initial industrial energy need, underwent a development period under a central public body, had a similar basis to objection and debate, has since reached a similar point in development, and is now focussed on the development of small hydropower development and license renewal. There is, however, also a degree of divergence between the two countries resulting from differences in topographical characteristics, national energy needs, profile of precipitation input, and the role of regional and municipal government.

Moreover, it is acutely demonstrated here that an additional critical aspect to this dynamic results from the interaction of multiple contextual elements, which can combine to present specific pressures on regulation and measures to obtain environmental targets. In this regard, this work crucially demonstrates how the connectivity between disciplines, scales and trends, be it natural resource characteristics; stage of resource development; regulatory characteristics; or, wider energy needs, can shape regulatory challenges.

This comparative assessment provides a valuable contribution to the research community by considering a number of diverse yet interlinked elements, such as the wider natural resource and energy context, uptake trajectory, and resulting hydropower characteristics. In this way the research has a very broad appeal, offering insight to a number of fields, both in the UK and internationally.

One specific contribution it makes is to draw together research into the changing role, challenges and governance of hydropower in Norway (Knudsen and Ruud, 2011) with the changing regulatory approach (Reid et al., 2004; 2005) and historical application of environmental flow in Scotland (Black et al., 2006). Although varying slightly in their focus, the current literature seeks to engage with themes of hydropower governance in a changing world. By explicitly linking energy and environmental paradigms, however, and offering an international comparison, this research chapter makes a further novel contribution to this field

Much of the research on hydropower in Scotland is rightly informed by the key study published by the economic historian Peter Payne (1988), which provided an in depth account of its emergence and development through the Hydro Board phase of expansion. To consider the current and future context and challenges for hydropower in Scotland, and indeed Norway, however, it is again demonstrated here that we need to broaden the scope of attention, placing it within a regulatory and renewables context. It is suggested here that this chapter therefore presents a natural progression in the study of hydropower, and so provides an interesting and innovative approach to an increasingly interdisciplinary subject.

In examining and engaging in the phases of hydropower regulation and mitigation in Scotland this chapter reinforces Reid et al (2004; 2005), but also provides an update and further orientates it in the renewables context. Likewise, it identifies and compares a similar mitigation progression in Norway. Furthermore, by looking at the case of the 1962 Strathfarrar-Kilmorack development, this chapter is also able to develop some elements of Black et al. (2006) where there was previous uncertainty regarding more nuanced detail to flow agreements, and gaps in knowledge regarding the goals and underlying decision making behind NoSHEB flow agreements.

Indeed, through identifying and examining the dominant connectivity agenda in NoSHEB schemes, this research draws on and reflects the emergence of specific themes in the academic literature of impounded rivers (e.g. Petts, 1984); it therefore links academic literature and applied practice. Ultimately, by informing this academic field that looks at the changing application of hydropower mitigation, given the flow legacy of hydropower in Scotland, this research engages and develops understanding about the long term implications of certain approaches, context and specific decisions.

The historical emergence of hydropower in Scotland, and continuing changes in its wider context, have shown to be significant in shaping its environmental and sustainability outcomes, meaning regulation has to be quite responsive to meet sustainability needs in a changing world. To ensure regulation is better informed and equipped to operate against this dynamic, it is necessary to understand the significance of, and connectivity between, these external factors. By taking a number of specific high profile regulatory challenges, examining how they are shaped by the changing wider context, and gaining further insight through a comparison with Norway, Chapter Five makes a useful contribution to the regulatory field.

It has demonstrated that whilst vastly different in the number of schemes and national installed capacity, there are parallels in the experience and trajectory of uptake between the two countries, and that they have now reached a similar point in development. Through providing this comparison, and highlighting the resulting shared experience, this work has value in creating a basis to dialogue and learning, where regulatory bodies may benefit from reflecting on wider experience internationally.

Against the historical emergence of hydropower, renovation, modernisation and upgrading of old power stations is often less costly than developing a new power plant, and can lead to more efficient environmental outcomes (IPPC, 2011). To examine the issues of water license revision in both countries is in itself a novel and timely exercise due to its current and ongoing delivery across the WFD RBMP cycles for both countries. Section 5.4 clearly highlights that whilst the WFD is a standardised framework across all member states in the EU, consideration of national needs is paramount and facilitated through the 'significant adverse impact on use' dimension. Although this will be known to respective licensing bodies, learning from the context and resulting approach of other member states, here Scotland or Norway, is also significant as a learning tool to help reflect on national context and requirements. Similarly, in the context of European led policy, this finding adds a timely reminder for the necessity to consider national needs and pressures to deliver sustainable outcomes. Fundamentally however, this section contributes a clear example for policy makers of how a changing energy context can shape the way environmental challenges are approached, and even constrain the regulators' ability to deliver environmental improvements.

Building on the existing Scottish literature (e.g. Reid et al., 2004; 2005; Black et al., 2006), this chapter has provided a similar examination of the progression in mitigation application in Norway. Provided as a comparison, these elements are useful for regulators to reflect on the experience in their country, consider how certain standard approaches have evolved, and potentially challenge assumptions and entertain alternative approaches. For example, Norway has a history of public ownership and local decision making relating to hydropower, which has shaped mitigation approaches and supported regional strategic planning. With a recent increased role for local authorities in the approvals process, Scotland could potentially learn from the Norwegian experience in this way. In addition, whilst sharing many aspects of mitigation historically, Norway is shown here to have become more progressive and targeted earlier than Scotland, certainly before the advent of the WFD. Whilst perhaps not of large significance, this information could act as a catalyst to review barriers to changes and improvements in approach, where inertia and a reliance on existing approaches can be overcome to deliver more effective regulation.

The examination of small and micro hydropower regulation and outcomes adds further value for regulators to reflect on what is one of the main areas for future growth in Scotland and Norway. Although presenting a similar regulatory pressure, the examination in chapter five suggested that there is divergence in approach between the two countries, with Norway taking a lighter touch and making a greater use of strategic spatial mapping.

Given the central role of hydropower in Norwegian energy needs, it is understandable that there is a regulatory culture of strategic mapping to support regulatory licensing and decision making, dating back to the 1980s. Whilst it is shown here that this is in places occurring in Scotland, it is an area that could be pursued more widely to support more integrated and strategic decision making that can serve to reduce the accumulative impact that this scale of development can have.

Chapter five has provided the opportunity to consider the historical emergence and continuing development of hydropower in Scotland against the experience and trajectory in Norway. It is felt there is a strong basis and rationale for this comparison, with both countries sharing a similar historical profile and more recent renewables context in the EU, which provides even greater insight and value.

There are however a number of large differences between the countries, such as in installed capacity and role of hydropower in the national energy mix, which could be viewed as limiting the usefulness of the comparison. Nevertheless, this research seeks to utilise these differences positively, to examine alternative contextual forces and resulting outcomes, enabling a rejuvenated assessment of both countries.

It is also acknowledged here that with this wider thesis focussed on Scotland, Norway present an aspect that is much less familiar and consequently could present a bias or raised chance for research error. To address this, and to focus and orientate the research, academics and government officials in Norway were consulted at the outset. Additionally, in this study, rather than being the main focus, Norway is also used more as a comparative instrument to assess the trajectory and characteristics of Scotland.

Through that comparison it has also proved challenging to obtain data and information of the same format and nature for the two countries, such as was the case when characterising and categorising hydro. It is felt that whilst this may detract presentationally from the analysis provided, it does not lessen the value of the comparison as the thematic content, general subject matter and thrust of the information remains the same.

To act as a research control, this comparison benefits from both countries having a similar hydropower trajectory, and a shared stage of development and future outlook. Whilst the future uptake of hydropower is fairly clear, being focussed on small and micro scale developments, uncertainty exists in both countries, especially Norway, about the role and implications for hydropower regarding the increased role and penetration of renewables nationally and Europe wide. This presents a large knowledge gap and potential area for further comparative research, as both countries may have to reassess the role, operation and potential implications of the hydropower operation.

6.4 OVERALL CONTRIBUTION

Hydropower in Scotland emerged and continues to develop against a changing wider energy and governance context, which shapes its characteristics and sustainability outcomes. More recently however, with Scotland orientating itself as a leader on climate in Europe, and also water governance under a hydro nation (Scottish Government, 2012b), hydropower regulation must now support the delivery of high profile binding EU targets on renewables, whilst also meeting similar obligations to protect and improve the ecological status of water bodies.

As Scotland undergoes this energy transition, moving to greater energy and potentially political autonomy, this thesis engages with the lack of policy harmonisation (OECD, 2011) yet acknowledged potential for water trade-offs from energy policy objectives (Volkery et al., 2011). Utilising an interdisciplinary, longitudinal perspective, by identifying and engaging with these linkages, and creating dialogue between disciplines and scales, this thesis seeks to inform the pursuit of sustainable renewable energy through policy and regulation. Delivering three stand-alone research chapters that each consider a different aspect but contribute to the overall thesis, this research provides an innovative and timely assessment of the influence a changing energy and governance agenda has had on hydropower outcomes in Scotland.

A key overall trend identified, examined and presented through this research is the growing influence the wider renewables agenda, felt through specific energy trends and policies, has on hydropower regulation and the delivery of environmental objectives. This is seen in all three research chapters, but is found to result in both positive and negative outcomes for sustainability. Overall, therefore, the renewables agenda has presented synergies, such as through RO eligibility encouraging scheme renewal mirroring WFD goals, and trade-offs, as seen with the lack of strategic planning within FiTs.

Acknowledging that further large scale hydropower development is unlikely, this thesis has explicitly sought to examine how the continuing trajectory of increased renewable development, through other technologies in Scotland, will feed back to provide unforeseen outcomes for hydropower. Interestingly, this transition is where two of the largest synergies or 'win-win' outcomes arise for water regulation. Namely, as is suggested in chapter three, that an increasing contribution from wider renewables moderates the reservoir level variability at Cruachan, creating more viable littoral conditions. Then secondly, that an increasing output from other renewable technologies means that the hydropower contribution is proportionally decreasing, making environmental gains from licence renewals more acceptable and so more readily achieved.

Indeed, despite the high profile energy transition towards greater low-carbon and renewable generation in Scotland, the UK and across Europe, there has been insufficient appreciation in academic or regulatory arenas regarding its potential feedback and implications for hydropower and the delivery of objectives for the fresh water environment.

Figure 6 provides a simplified visual representation of the novel linkages and connectivity that this thesis identifies and examines. Firstly, here we see represented that there is already a general appreciation (grey arrows) of how climate change can directly affect the water environment; that the wider energy context can shape energy policy and in turn lead to a changing emphasis on certain renewable technologies; and also that hydropower, perhaps mitigated through changing regulation, can be detrimental for the water environment.

The coloured lines in **Figure 6** are the contribution in understanding that this thesis provides, through each of the three research chapters. Here we see through the example of Cruachan in chapter three (blue arrows), energy policy and trends determine the deployment of intermittent technologies such as wind power, which shapes operational and in turn environmental outcomes from hydropower. Chapter four on incentive mechanisms (red arrows) contributes a timely examination of how specific energy policies can shape outcomes for the fresh water environment through hydropower. Finally, chapter five that looks at Scotland and Norway (green arrows), highlights how the wider energy context, through interacting elements such as resource characteristics and availability, in addition to energy demand profiles can shape hydropower scheme characteristics but also regulatory approaches, leading again to specific outcomes and implications, both positive and negative for the fresh water environment.

In conclusion, it is this acute demonstration of the connectivity and linkages between disciplines, namely energy and water policy, and scale, with national energy trends influencing scheme level outcomes, that are the main contributions of this thesis. By highlighting these linkages, this thesis is to be seen as a first step in addressing these uncertainties and supporting a more integrated (e.g. Bührs, 2009) and sustainable hydropower and renewables governance framework.

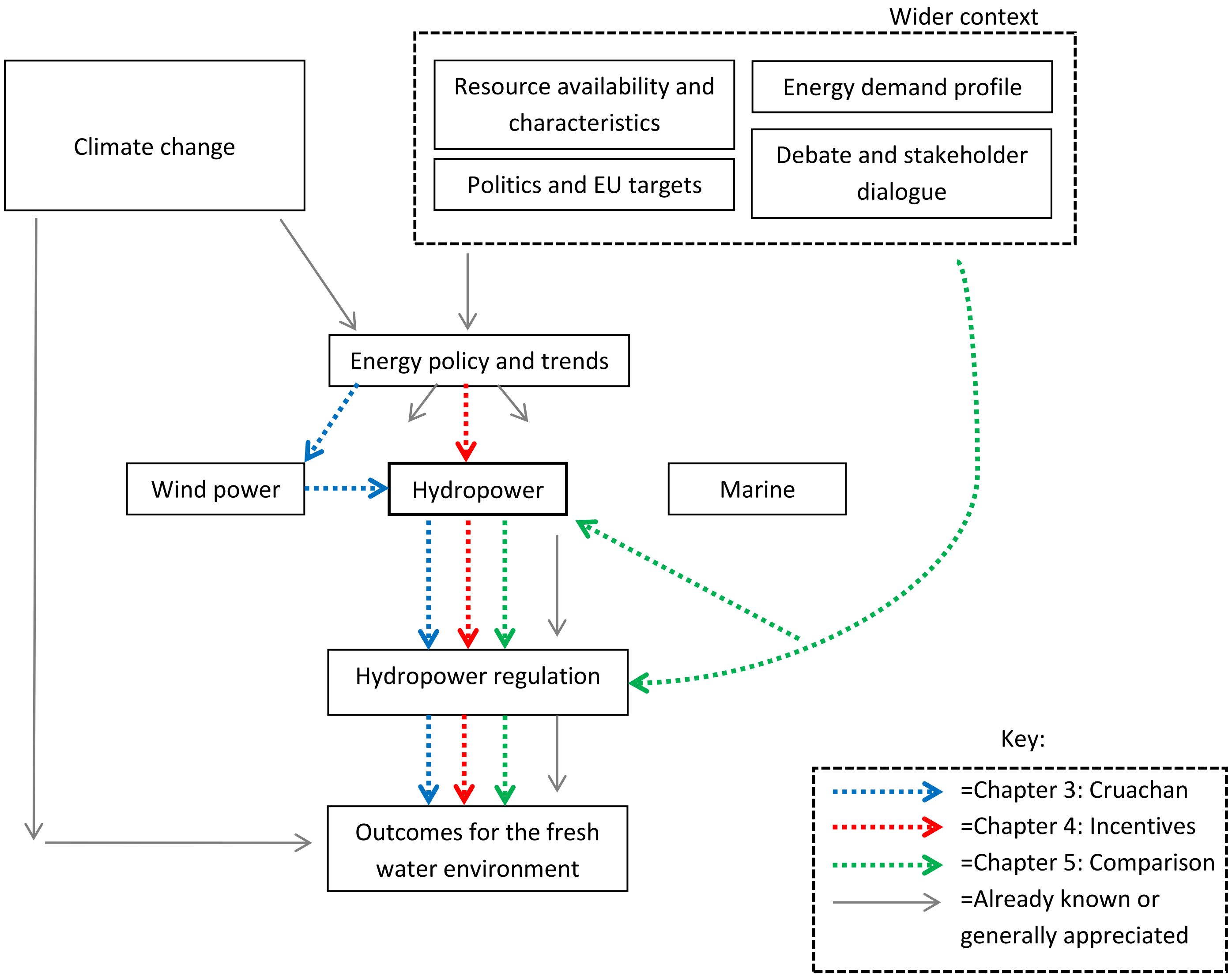


Figure 6: Visual representation of connectivity provided by research chapters in this thesis

Chapter SEVEN: CONCLUSION

7.1 AIMS AND MAIN CONCLUSIONS

The aim of this research is:

To provide an interdisciplinary understanding of the long term sustainability of hydropower in Scotland, identifying the influence of a changing energy and water context on hydropower characteristics and challenges.

The main conclusions from this research are:

- That the changing wider energy mix towards an increased contribution from potentially intermittent renewable technologies such as wind power has contributed also to an alteration in the operational characteristics and reservoir variability profile of Cruachan pumped-storage scheme, presenting positive outcomes for littoral habitats.

- That whilst not operating in isolation, through their eligibility criteria, financial reward framework and timing, renewable energy incentive policies shape hydropower characteristics and sustainability challenges, providing trade-offs and synergies for hydropower regulation.

- That the characteristics, and especially interaction of wider contextual elements such as topographical characteristics, national energy needs, profile of precipitation input, and the role of regional and municipal government have led to a degree of divergence in hydropower outcomes and challenges between Scotland and Norway.

7.2 CONTRIBUTIONS AND RECOMENDATIONS

Against high profile climate policy and increasing uptake in renewable generation across Scotland, the UK and Europe, this thesis has provided one of the first responses to uncertainty regarding how this energy transition can influence hydropower characteristics and outcomes for sustainability. By providing an interdisciplinary and longitudinal critical evaluation, this research presents a timely and innovative contribution that:

- Identifies the linkages and creates dialogue between energy and water policy, across multiple scales

- Highlights the influence and implications of a changing wider energy mix for the water environment through pumped-storage hydropower

- Shows that hydropower regulation has moved on to a new phase in development, to one that now must increasingly reflect and consider wider energy goals and trends

- Adds further detail and understanding to literature regarding the development and decision making behind compensation flows and mitigation in Scotland

- Provides an innovative account of the development and characteristics of hydropower under the three main renewable incentive mechanisms in Scotland

- Adds to understanding regarding the energy outcomes from incentive mechanisms, and is the first to bring in consideration of the resulting implications for water environment sustainability.

Arising from these outcomes, this research is able to make a number of recommendations for hydropower regulation and governance, and research and theory, to inform the delivery of sustainable renewable energy.

7.2.1 Recommendations for research

- To further explore and examine the uncertainties regarding feedback outcomes and pressures on the water environment arising from the continued transition to a low-carbon and renewables dominated energy system.

- In future research to build upon the explicit linkages between disciplines and scales presented here, to provide a more solid evidence base with which to inform sustainable and integrated energy policy.

- To apply the principle developed here that hydropower characteristics and in turn implications for the water environment, are shaped by an often changing wider context, to inform the delivery of sustainable renewable energy in a changing world.

7.2.2 Recommendations for policy and practice

- For energy policy to acknowledge and reflect that alongside the issues of security of supply and efficient integration, the increasing proportional contribution of renewables has implications for grid balancing elements, and in turn can influence ecological outcomes through hydropower.

- That through the early development of new energy policy, or alterations to existing policies, officials seek to engage with environmental stakeholders and regulators, to at best integrate issues of hydropower sustainability into the policies, or at least flag potential pressures to regulators.

- That regulators and the water sector engage in dialogue regarding the role and challenges for hydropower reservoirs, especially those of peaking schemes, to inform future use, change and what damages are acceptable to deliver societal goals.

- That utilising the specific examples, or the type of connectivity identified in this research, there be overall greater dialogue and engagement between energy policy and water regulatory bodies, to support greater sustainability for renewable energy.

7.3 CLOSING REMARKS

Up until now, despite the acknowledged potential for environmental trade-offs from energy policy (Volkery et al., 2011), there commonly has been a lack of integration between energy and water policy (OECD, 2011), presenting a disconnect in governance and the opportunity for unsustainable outcomes.

Whilst there is research on the role the historical emergence and continuing development of hydropower has had on hydropower characteristics in Scotland (e.g. Payne, 1988; Black et al, 2006; Reid et al, 2006) there is little understanding regarding the effect and implications of the more recent renewables agenda, and the influence of specific policies and trends. Research into implementing mitigating environmental flows and improvements has more recently begun to consider site specific operational characteristics and open up to reflect interdisciplinary aspects of use (e.g. Richter et al., 2006; Bruno and Siviglia, 2012), but it is argued here this scope does not go far enough.

Through identifying how wider energy trends and specific policies have influenced hydropower outcomes and scheme level regulatory challenges in Scotland, this thesis argues that there must be an increased consideration of these linkages and previously external energy characteristics, in regulation and research, to support the delivery of sustainable renewable energy.

As Scotland seeks to deliver on renewable energy targets, but also protect and enhance the fresh water environment, this innovative and timely research identifies the linkages and creates dialogue between energy and environmental disciplines and scales, to inform challenges of sustainable renewable energy. Through some specific examples, this research has demonstrated that a changing wider energy and policy context continues to influence hydropower characteristics and in turn challenges for sustainability.

It is anticipated that this research will feed into work to realise, protect and deliver on the high value of the water environment and sector under the "hydro nation" agenda (Scottish Government, 2012b). Principally however, this work will be part of an emerging field that considers the continuing sustainability hydropower in the context of a changing wider renewables agenda, whilst is also able to inform integration and dialogue between energy and water policy at multiple scales.

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