Abstract—The Icelandic power system is based primarily on hydroelectric and geothermal generation. The system has large resources compared to the size of Iceland’s economy. The main utilization practice for electrical energy hitherto has been bulk Energy Intensive Industry (EII) with relatively flat and constant load. A possible future interconnection to neighboring countries via High Voltage Direct Current (HVDC) submarine cable could affect dramatically the operations planning framework, for instance with possibilities of linking to wind power, local and/or foreign and short term markets. This should affect factors such as operation strategies for hydro system and the planning and operations tools needed to realize this rent.

Planning tools and modeling for hydro dominated systems may in some respects inherently be more complex than those of thermally dominated systems, due to the time-interdependence associated with reservoir storage and various constraints [4]. In this paper we give an overview of historical and current modeling practices used both as a tool to form system expansion policies and operations strategies in the long, medium and short term. The basic time frame requirements for such tools are discussed in this paper and how the may evolve in the future in terms of methodology and other important issues. Conclusions will be drawn regarding these planning tools and the future planning and operations framework in such a system, especialy the time frame issue.

The long and medium term hydro-scheduling problem has been investigated since in the early part of the 20th century [14], applying various optimization and iterative simulation methodologies. The practices applied in the Icelandic system have traditionally been based on Scandinavian approaches, such as those originally suggested by [9], [17] and [2]. These methods in hydro dominated systems have been based on an iterative calculation of water value tables based on iterative dynamic programming like algorithms. Future methodology may involve LP or SDDP [16], but with a short term considerations (DTM, see below) to certain extent as outlined in this paper.

I. INTRODUCTION

Iceland is blessed with a large amount of renewable hydro and geothermal energy resources as compared to the size of its economy. Although hydroelectric and geothermal resources are most important, wind energy resources have recently come increasingly into focus. Only a fraction of all these energy resources has been harnessed so far and the wind energy resource has not been developed at all. This resource is, however, starting to raise interest at this time.

Further utilization of these resources will depend on market development and other constraints which may include new loads, such as instance EII loads and other bulk sales. Furthermore, connection to distant electricity markets may become a reality with a future HVDC submarine connection, (580 km). Also shown are proposed connections as a part of the North Sea Supergrid [13].

Environmental and economic constraints will undoubtedly apply increasingly in the future as it will be important to consolidate various concerns of this nature. Questions relating to tourism and nature preservation have been increasingly raised by various groups. This might limit the possible development and various economic issues weigh the cost of these resources compared to other options.

In this paper we will address various concerns regarding options in time frame and time constraints for such operations planning models. These issues include short term phenomena such as wind variability, and long term issues for planning and even resource assessment within a hydro dominated power system. The purpose of the paper is to suggest some new developments in operations and expansion planning models for a small island system such as that of Iceland.
The paper is organized as follows. In section II we will briefly review the Iceland power system, loads, market and energy resources as a basis for further discussions. In section III we will discuss the general hydro operations problem and address some key questions on approaching the question of time frames. The issue of times scales is important in future operations and expansion planning methodologies in relation to the limits to computational resources. This is especially important when integrating wind energy resources into the system model where the wind phenomena occur on a short time scale, while the hydro system moves in many respects much slower. In section IV we summarize the conclusions and discuss the results and how they might be applied in the case of Iceland. Finally the paper is concluded with an acknowledgement and a references section.

II. THE ICELANDIC POWER SYSTEM

We start with an overview of generating capacity and energy, loads, markets and resources. This is to provide a basis for approaching and applying a operations planning methodology in this small island hydro based system. We should also keep in mind the geothermal component and a possible future HVDC interconnector.

A. Existing generation capacity in the Icelandic system

The system consists of a number of hydro and geothermal stations. The largest is the Kárahnjúkar plant (690 MW) followed by Búrfell (270 MW), Hrauneyjafoss (210 MW), Blanda (150 MW), Sigalda (150 MW), Sultartangi (120 MW), Sog (90 MW in 3 plants), Vatnsfell (65 MW), Laxá (27 MW), Andakill (8 MW) and Elliðaárhú (3 MW). Geothermal stations include Hellisheiði (303 MW), Nesjavellir (120 MW), Reykjanes (100 MW), Svartsengi (75 MW), Kráfla (60 MW) and Bjarnarflag (3 MW). Thermal fuel station are only smaller units such as diesel generators only to be used intermittently for back-up generation.

Iceland’s total installed capacity is more than 2 GW, where the largest generating company, Landsvirkjun has an installed capacity of 1,895 MW, with 1,797 MW in 13 hydro stations and 63 MW in 2 geothermal stations in addition to 35 MW at one fossil fuel-powered reserve gas turbine station [11].

B. Current electrical energy generation

Iceland’s total electricity production in 2010 amounted to about 17 TWh/year, of which Landsvirkjun’s the largest generation company generated 74% or 12.5 TWh/year. In 2010 a total of 73.8% of electricity in Iceland was produced with hydro power and 26.2% with geothermal power. Landsvirkjun’s share in electricity production is 96.2% for hydro power and 11.5% for geothermal power. Over 96% of electricity produced by Landsvirkjun comes from hydropower, while geothermal power contributes some 4%. In addition to Landsvirkjun there are Reykjavik Energy and HS Orka, with geothermal generation [11].

C. Recent growth in capacity and energy

Primary energy utilization is not discussed here (Space heating, transportation etc.) except to mention the rapid growth shown in Figure 2 which includes both indigenous hydro and geothermal energy and imported fossil fuel energy.

The insert in Figure 2 shows how different fuels are substituted in Iceland in the 20th century, first from peat to coal and then to oil and finally to renewable energy. Also shown is the rapid increase in energy use, in particular the expansion of EII in the last 10 years.

Figure 3 shows the rapid expansion in electricity consumption with the “general demand” (for Landsvirkjun only), i.e. residential demand and light industry, while the bulk of the explosive growth is the EII, such as the Alcoa plant which started in 2007.
D. Electrical loads and markets

In Iceland there are basically 3 options for realizing the economic rent of the resources. This includes (a) general local demand, (b) new local industrial customers (EII) and (c) export to a foreign electricity market. However since the general demand is fairly constant, (Figure 3), options (b) and (c), i.e. the EII and export are the basic possibilities.

Option (c) or the export through a HVDC submarine cable is specially interesting (See Figure 1). Such an exchange could involve an electricity market or bilateral contracts with specific customers. The NORNED cable is an interesting model, and the prospects to connect to a spot markets with short term price and quantity variations have evoked increased interest [8]. Potential cable routes are shown above in Figure 1.

E. Future resources and capacity expansion

We review here very briefly the amount of untapped hydro and geothermal resources in Iceland. Various estimates exist on the total resources, both hydro and geothermal [3]. A new master plan (Phase II) has been presented [15], with energy generation capacity estimates considering environmental restrictions. All such estimates are subject to uncertainty. However the following figures are often quoted as approximate [7]:

- Hydroelectric resources with environmental constraints: 30 TWh/year
- Geothermal resources with environmental constraints: 35 TWh/year.
- Total geothermal and hydro resources: 65 TWh/year total where already 17 TWh/year are already utilized as noted above.

Wind resources are uncertain, since few estimates have been performed on the wind resources. Therefore no figures will be explicitly stated on the wind energy resources. There is, presently an ongoing study to map out the wind resources along with their geographical distribution [10].

All these estimates are subject to considerable uncertainty but the main conclusion is that considerable renewable energy resources are presently available. Therefore sophisticated operations and planning models will be needed to maximize the future economic benefit of these resources in the electricity markets of the future.

III. OPERATIONS PLANNING AND MODELING REQUIREMENTS

In a future system with dominating time interdependencies and hydro reservoirs as energy storage coupled to geothermal and wind energy derived from uncertain natural phenomena, sophisticated scheduling models are likely to be of increasing importance. This is a small and seemingly complicated power system to operate when compared to a pure traditional thermal system, or a hydrothermal system with a minor hydro component. The small size does not help, since a small system may not be able to support the sophisticated procedures needed for optimal operations of larger systems. General tools from other systems are likely to be out of line in many respects, since each system is often basically unique, and this most likely applies to the small Icelandic power system. Therefore methodology from other systems may not be directly applicable. In addition it is uncertain what role competition and market forces can play with very few players and prevailing market power of the large players.

A standard mathematical programming formulation of the hydro operating problem, as shown for instance in [12, 2, 5, 14, 16] and outlined in [6], usually assumes a standard discretization of the state space in terms of the time variable. Time is decomposed into a number of fixed time steps throughout the planning horizon. Basically 3 categories are common: Long term, medium term and short term scheduling/optimization as indicated to the left in Figure 4 with the appropriate interaction between models.

In this paper we will argue for a dynamic time frame where the length of each time step may be variable. This is an interesting approach when adapting the model to both the fast and slowly moving short and long term phenomena in the system.

A. Dynamic decomposition of the time frame

As is well known, hydroelectric power is one of the most flexible forms of power generation, where the turbine generator sets can respond to load variations quickly in a matter of seconds or minutes. This is opposed to, for instance, nuclear or coal or even geothermal power, where load following is more problematic calling for a relatively constant load.

When wind power is introduced into a hydro based system, it is exactly this flexibility that allows for the "marriage” of the wind/hydro resources. Furthermore, with the energy storage in the reservoirs, an economic energy product is introduced.

As with the introduction of wind power in systems, such as in Scotland and the North Sea, (Supergrid [13]) where flexible hydro in general has become increasingly valuable, we expect economic benefit from integrating these resource in the case of Iceland.

However the problem is the wide varying time scales occurring in the system and matters are made even worse by adding wind to the hydro with dynamic phenomena occurring...
within minutes as opposed to the hourly fluctuations in purely hydro systems.

This back-up function can easily be extended through an HVDC submarine link, once such a connector is in place. Therefore hydro from Iceland, through a cable, can be used to back up wind resources elsewhere. Alternatively, hydro generation in Iceland could back up and generate against local wind generation in Iceland, but the combined hydro/wind "product" exported and sold locally or through a HVDC connector.

Wind/hydro integration may therefore introduce superad- 
ditive value to this specific product, higher than the sum of its parts. An optimization or simulation modeling effort is however needed to estimate this value. The Icewind project [10] is an example of such an experiment.

Next we discuss the time frame issue in optimization of a combined hydro/wind system. First traditional fixed time frames are outlined and then we argue that a dynamic de-
composition of time is called for where the time step is continuously adapted to the variability of the wind and hydro phenomena. This is a key issue in appropriate approximations leading to an efficient model.

B. Time frames in wind/hydro system operations models

The modeling objective as always is to grasp important aspects of the system under study, but staying within practical computation resource constraints both in off/on-line studies. Since models encompassing all dynamic phenomena on all time scales is generally not feasible, system simulation and optimization models have traditionally been classified into 2 or 3 categories in terms of time frame, that is: long, medium and short term models. This is to break down the computation burden by concentrating on each aspect of the problem at a time.

However, with today’s increased computational resources, parallel supercomputers etc. coupled with an increased need for a close interaction between the new short term phenomena such as wind variability and long term reservoir dynamics, we argue that a dynamic time frame may be the logical and feasible approach since hydro optimization models for all time frames are basically the same. This is subscribing to the philosophy of gradually populating a coarse state space in terms of time.

Let us start by summarizing the traditional fixed time step approaches as outlined in [6]:

1) LTM or long term models, with a time step of 1 or 2 weeks and a planning horizon of years. The input is a weekly inflow or a stochastic process of future inflow. The seasonal load and inflow fluctuation are well covered resulting in reservoir release weighing the decision to store water by running backup resources now against a possible shortage later. Important optimization methods include Linear Programming (LP) and Stochastic Dual Dynamic Programming (SDDP) [16].

2) STM or short term models, with a time step of 15 minutes up to a 1-2 of hours and a planning horizon e.g. of 1 - 2 weeks. The daily load variations are primarily addressed, perhaps with accurate modeling of system transmission and head losses. The rapid wind variations can be covered here and fit right in. The result is a daily generation schedule and can readily interact with a short term spot market. The STM may use similar optimization techniques, as LTM, but different approximations are usually made how variable head is modeled and how unit commitment (start/stop) is accounted for.

3) The less common medium term models, MTMs lie in between LTM and STM, to bridge the gap, with a typical time step of say 6-24 hours.

C. Load duration, chronology and mixing of STM and LTM

Again, Figure 4 (to the left) shows the above 3 types of models as separate blocks, interacting with iterative information exchanged between models. Which variables are candidates for such exchanges? Perhaps, first are the dual multipliers such as water values or values of other constraints (Megawattage or transmission constraints). Other candidates include primal variables such as reservoir contents or generated energy at the beginning/end of a time step.

In addition to standard time frame decomposition, it is possible to apply spatial decomposition. The system can be split into zones where LTM is sufficient in some zones where reservoirs levels and heads vary slowly but STM is needed in other parts e.g. with smaller reservoirs [6].

Therefore the "water" and "power" variables [6] may operate with different time frames and the "wind" variables have short term variations. For instance, heads and reservoir levels vary slowly but loads and generation has variations in minutes or hours.

These LTM and STM time frames for loads are illustrated in Figure 5 as a hierarchy in terms of breaking down time. In [6] several approaches to the interaction between the LTM and the STM were introduced. We give a short outline here of the approaches.

1) C1 - Continuous Load duration curve (LDC) by sorting 8760 hours/year into a continuous LDC and is denoted CLDC. Chronology is completely removed and as this approach is not well suited it falls outside the scope of hydro modeling.

2) LTM 1 is a traditional LTM without considering short term phenomena, with e.g. 12, 26 or 52 time steps. In this crude time resolution LTM chronology is maintained, while it is disregarded for the STM since it results in weekly averages.

3) LC2 assumes a LDC added in the week accounting for variations within each LTM time step. Chronology is still removed within the week and replaced by the LDC to represent the hourly distribution. The chronology for very small reservoirs with variable head is lost, but an estimate e.g for installed megawattage may be obtained.

4) LSIL assumes complete chronology in all periods for LTM, STM and even MTM with separate models or
model. (See Figures 3 and 5). Variables are assumed to be passed back and forth such as water values, average generation as in 5. LS1 is a very computationally intensive approach, if it is applied to all LTM periods and assumes fixed length time steps on 2 or 3 levels (LTM/MTM/STM).

5) LSC. This is a hybrid of the above with STM chronology used alternatively with an LDC. Some LTM periods would keep the STM chronology while LDC removes it in some periods.

D. Dynamic time frame models (DTM) with variable time steps

In this paper we suggest an adaptive dynamic time resolution as outlined in Figure 5(B) and thus forming a certain mixture of the above methods. The adaption should take into notice the constraint violations and STM/LTM variations. Since hydro optimization modeling representation is very similar regardless of the time frame, there may not be an apparent need to distinguish the methodology entirely between LTM and STM (Figure 4 left).

The above concept is illustrated in Figure 5(B). In the lower part, (B) we assume that a coarse resolution suffices when apparently no constraints are violated (Left part of the Figure). Perhaps LC2 approach can be used under these conditions to verify constraint violations.

For example, an LTM model with averages may suffice when wind capacity is below applicable transmission limits and installed hydro generation capacity is ample. This may be verified using an LDC approach. Alternatively, an LTM 1 approach can by used by simply smoothing the short term phenomena and using a daily or a week time averages in the corresponding time steps.

On the right of part (B) of Figure 5 (short term) capacity/power violations are clearly detected on e.g. box constraints. Then the time scale may be reduced to hours or minutes adapting to the constraint boundaries.

The idea behind this dynamic approach called DTM is to populate a finely graded state space in terms of the time variables as needed by the nature of constraint violations, gradually as computational resources permit. Therefore, for instance, sequential runs of a model may gradually fill the state space where new iterations will use dual variables or other primal information on constraint violation from a previous iteration.

IV. CONCLUSIONS AND DISCUSSION

A. General discussion

The conclusion from the above discussion is that to effectively address aspects of a complex power system with varying technical and operating characteristics, and considering the limits in scope and computation resources, a proper decomposition and resolution in terms of time frames is important. To effectively cover transmission and generation constraints with respect to e.g. the rapidly varying wind resources, load and spot markets, a proper representation of short term phenomena (STM) seem critical. It is concluded that since basically hydro optimization models are similar in the long and short terms a dynamic time resolution in the iterative process towards a convergence in solution may be a logical development.

B. Some conclusions and suggestions for further research

The following are the main points of this discussion paper:

- The selection of the actual time resolution in a model is a trade-off between model accuracy and computational resources.
- There is no inherent reason for fixed time resolution into the LTM, MTM and STM models and therefore it is logical to suggest a dynamic DTM approach.
- Wind resources and spot markets seem likely to pose new interesting challenges to traditional hydro based system modeling and operations.
- Model differences with a dynamic time step can include representation of losses and spatial selection of variables such as “water variables” and “power variables” as outlined in 6.

Figure 5. The upper part (A) shows a possible fixed and predefined time step decomposition into LTM and STM. The intermediate level of MTM is left out of the Figure but may be defined similarly. The breakdown can include chronological time, as shown in each level, or LDC information. One more level below with very short variations in minutes e.g. for wind energy (VSTM) could be envisaged. Part (B) of the Figure shows a dynamic time decomposition/model (DTM), where the time step size is reduced with rapid variations in variables and operational constraints are violated. Rapid variations with no anticipated violation of constraints do not call for a reduced time step as indicated at the left in part (B).
• LTM time scales have been used with good results for a hydro system without wind resources. With the integration of wind and spot markets STM can be incorporated in a model as a single DTM model.
• There seems a multitude of ways to decompose the time scale to assimilate short and long term phenomena.
• To address transmission constraints, generation constraints and head losses or losses in waterways, integrated STM or DTM seem important possibilities in the traditional LTM framework.
• The DTM approach suggest gradually populating the relevant part of a fine time resolution state space. Therefore in many respects this is similar to the philosophy of the SDDP approach [16].
• The DTM approach has not been tested on a specific system but the DPM philosophy is an open topic subject to at least this author’s further research.

Finally we will offer some suggestions of applying this philosophy in the Icelandic hydro-based power system.

C. Application potential in the the Icelandic system

In the past, a simulation and water value based iteration has been used in Iceland as an LTM backbone and as served well for the EII based environment of the past decades. It may be important to extend this to encompass a short term model by including an STM approach or a DTM as suggested in this paper in future modeling efforts. This is especially important if and when wind penetration becomes significant and/or short term hourly spot markets are introduced or connected to the system by a cable. As the system may have active transmission and generation constraints and short and long term reservoirs with variable nonlinear head losses, it seems to this author that a DTM philosophy or an LS1 or LC1 philosophies could be promising. These and others approaches should be investigated further by modeling experiments, prior to drawing any final conclusions for applicability in to a small hydro/renewable system like that in Iceland. It is hoped that the modeling experiments in the Icewind project [10] project and further research and other such future modeling experiments provide steps in that direction.

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