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The dynamics of technological systems integration: Water management, electricity supply, railroads and industrialization at the Göta Älv

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ABSTRACT

Today, technological innovation is often called upon to deliver solutions to the sustainable development challenges that the world faces. The integration of different technological systems is promoted as a main option for that goal. By integrating systems, waste from one system can be used as feedstock for another system, equipment can be used more efficiently by economies of scale, and/or the service that can be provided to customers, can increase.
Integration of technological systems is not just a technological challenge. Systems integration creates new social interdependencies which imply that the previously unrelated systems lose part of their autonomy. Autonomy of a system is a valuable asset that allows a system some flexibility when it is confronted with changing conditions. Integration implies that institutional frameworks have to be created to balance the interests of previously unrelated actors. Moreover, the technological as well as the social complexity of an integrating system increases, which makes it harder to manage.
This paper studies the process of systems integration and its related process of creating new institutional frameworks by analyzing the introduction of large scale hydropower in Western Sweden and developments that were triggered in this complex systems integration. In 1910, the first large scale hydropower station was opened in the Göta Älv river at Trollhättan. The hydropower station was close to the Gothenburg-Stockholm railway line, which was planned to be electrified. The seasonal excess of electricity was sold at a low price. This attracted industries that depended on cheap electricity, and Trollhättan became a center for metallurgical and electrochemical industry.
The hydropower plant owners aimed at completely regulating the river in order to optimize power production. However, this implied that the interests of riparians, agriculture, river transport and fisheries would become subordinate to power production. Creating an institutional framework for this integration lasted 21 years.
This historical analysis identifies three main elements which enabled (or impeded) systems integration. These were: spatial conditions that provided options for integration, expected efficiency gains in relation to the anticipated loss of autonomy for the integrating systems, social processes among the actors involved. Different degrees as well as different types of systems integration were discerned and the paper develops a typology of systems integration processes.

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1. Introduction: the importance of analyzing the integration of technological systems

Sustainable Development is the global challenge of our era. As the current affluence levels of the developed countries will probably also come within reach of the highly populated South Asian and Latin American countries, there is a pressing need to develop leaps in the environmental efficiency of production and consumption [1]. Systems innovations are often claimed to be the main route to achieve leaps in sustainability. Systems innovation has been studied starting from Thomas Hughes seminal work Networks of Power [2]. Large Technological Systems (LTS) became an important concept in the history of technology and in innovation studies. Especially the emergence and successive growth phases of LTS were deeply analyzed [2–7].

The integration of similar systems that reach each other by their expansion has been studied by a number of scholars not least in the case of electricity systems [8–10]. When similar systems meet, their integration can be beneficial for both, as it might enable higher service levels, lower costs, or increased reliability of service. However various economic and political problems can arise, and the systems might be "locked in" in (slightly) different trajectories for example in the case of the various national European railway systems as there are still considerable differences in gauge, signaling systems and electric power supply that prohibit efficient international transport, [cf. [11]]. It is important to note that when similar systems meet, the type of actors, and their 'actor worlds' are quite similar in nature.

Systems integration of dissimilar systems is quite different in nature. This form of systems integration happens when two systems (in general at the same place) increase their level of interdependence in order to reach a higher combined efficiency i.e. customer service/input of resources. This form of systems integration is nowadays often promoted as "*Industrial Symbiosis*" or "*Industrial Ecology*" and the Kalundborg industrial site in Denmark often serves as the exemplar [12]. Industrial Ecology started as an attempt to make the metabolism of the industrial society more efficient [13]. The benefits that are perceived to be achievable by the symbiosis of dissimilar systems often come at a cost, i.e. in order to achieve the benefits the systems have to give up (part of) their autonomy and flexibility. Moreover, as the systems are dissimilar, their organizations and cultures might differ much more than in the case of integration of similar systems. The social and technological complexity of systems is growing by integration. Perrow [14] emphasized the limited predictability of the interactions in complex systems with tight couplings and therefore made a plea for prudence regarding complex systems.

In Hughes' approach of LTS, the boundaries of a system are defined by the control that the system builder can exert on its constituent element. Hughes' analysis is then focused on the growth of a system, building up momentum, and dealing with the barriers that the system's environment creates [2]. In this approach, the system's environment is primarily adverse: it is the world to be conquered or to be defended against. However, systems integration blurs this picture: in systems integration processes, system builders aim at creating synergy but in turn they have to adapt and allow some of their elements to be partially controlled by other system builders. There is no clear cut theory describing this specific phenomenon. One might expect technological determinist concepts of innovation to analyze systems integration in terms of geographic/scientific/technological necessities while constructivists would emphasize the actors' perceptions and their ability to create the new socio-technical arrangements of integrated systems.

The integration of systems might show various degrees. At its lowest level, it might involve minor technical arrangements that hardly exceed a volatile market relation between non-integrated systems. At its highest level, it might involve a complete joint control of the systems and operations. An example of systems integration is that of a district heating system with an electricity production system. This integration might vary from the use of waste heat of the power station by the district heating system to a fully integrated system with joint control of a Combined Heat and Power Plant (CHP), physically linking the district heating system to the electricity system.

Although the increased efficiencies that might be achieved by systems integration appear tempting, there are various disadvantages for the actors involved:

- Integration increases sunk costs (investments in specific hardware) as well as 'social sunk costs' (investments in setting up new arrangements)
- Systems integration, like all processes of technological change, involves the risk of unforeseen effects such as unintended interactions between parts of the systems.
- Systems integration might diminish the autonomy of the constituting systems, i.e. it might hinder them to deal with future changes.
- Systems have cultures [2]. Systems integration requires the cooperation of actors with different cultures, which might be a cause for problems.
- Systems integration might make the integrated systems harder to manage, as the increased complexity of the integrated systems and a higher number of tight couplings between system elements might lead to improper reactions to rare systems conditions, i.e. accidents caused by improper control [Cf. [14]]

These disadvantages are major factors for the organizations that own/manage the systems that are integrated. But not only for them: society at large might be affected by large accidents. A major long term effect of systems integration might be an increased "lock in" of the integrated systems. As a result, the integration of systems in order to contribute to sustainable development might later turn out to have created a barrier for further improvement towards this goal.

Besides the direct advantages, the integration of systems might also have longer term additional positive effects:

- The larger combined size of the integrated systems might enable it to access or acquire additional resources